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Use of Infrared Temperature Sensor to Estimate the Evolution of Transformation Temperature of SMA Actuator Wires

Rodrigo Amaral M de Andrade[1] and Tadeu Castro da Silva[1,2]*

[1]Laboratory of Opto-Mechanics (LOM), Department of Mechanical Engineering (PGMEC-TEM), Federal Fluminense University (UFF), Rua Passo da Pátria, 156, Bloco E, Sala 210, 24210-240 Niterói, Rio de Janeiro, Brazil

[2]Additive Manufacturing and Tooling Group (NUFER), Federal University of Technology - Paraná (UTFPR), Curitiba, PR 81280-340, Brazil

***Corresponding author:** Tadeu Castro da Silva, Laboratory of Opto-Mechanics, Department of Mechanical Engineering, Federal Fluminense University, Brazil

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ABSTRACT

Shape memory alloys (SMAs) can be used as actuators with the application of temperature gradients, altering the material's crystallographic phase while it reaches transformation temperatures, and extends macroscopically. Measurement of temperature is of fundamental importance in thermomechanical characterization and many applications of SMAs. The use of infrared thermography is often the most suitable technique or the only possible way to measure the temperature of the shape memory element. This measurement depends on knowledge of the emissivity of the material in question. One could measure the temperature of SMA by using any standard temperature measuring instrument, except when used on small size scales, such as actuator wires. In this work, we focus on the application of a specific experimental non-contact technique for measuring temperature in NiTi thin wires, and in this way, to determine transformation temperatures during thermal cycling under constant load. NiTi wire specimens with 500 μm diameter were subjected to thermal cycling and investigated for the transformation temperatures, hysteresis loops, and the linear relationship between the austenitic (As and Af) and martensitic (Ms and Mf) transformation temperatures under applied stress of 150 MPa. The wire temperature and strain values were correlated in hysteresis loops, by estimating the phase transformation temperatures with the tangents of the curve. The result indicates that IR (infrared radiation) sensors can be used to estimate the temperature of a thin SMA actuator, despite its difficulty in focusing the measurement showed an average error of ± 1.5% approximately.

Keywords: Biomaterial; Actuator Wires; Infrared Sensor; Shape Memory Alloys; NiTi; Temperature

Abbreviations: SMAs: Shape Memory Alloys; Ms: Martensite Start; IR: Infrared; PWM: Pulse Width; Modulation; PC: Personal Computer; HDD: Hard Disk Drive; SME: Shape Memory Effect

Introduction

Shape memory alloys (SMAs) can undergo temperature-induced phase transformation processes and can be used as actuators. The temperature gradients of SMAS through the forward and reverse martensitic transformations, result in fully recoverable deformations of values up to 8% of their initial length, which explains the successful use of these alloys as actuators. There are four important transformation temperatures in the process of heating and cooling SMA: the martensite start (Ms) and finish (Mf) temperatures that occur during cooling and the austenite start (As) and finish (Af) temperatures that occur during heating [1]. SMAs presents two exceptional thermomechanical behaviors that can be used for the development of many applications: the shape memory effect and superelasticity. The shape memory effect is characterized by reversible deformation under thermal loading due to thermoelastic martensitic transformations. The martensitic transformation process that occurs during SMA loading is strongly dependent on temperature [2]. Thermal cycling through the forward and reverse martensitic transformations could generate degradation and defects in the material, which could be a structural and functional fatigue failure. In the case of SMAs, thermal cycling has as a consequence the loss of the shape memory effect [3], also known as actuation fatigue, as well as changes in material properties, such as the reduction of characteristic transformation temperatures [4,5] and the latent heat of phase transformation [6].

Performing meaningful experiments on SMAs is not a trivial matter, since they are extremely sensitive to their environment. Additionally, it is not possible to use thermocouples or other standard temperature measurement instruments on thin wires. Thus, it is common to use a relationship between the electrical current applied to a wire and its temperature for the purpose of estimating the phase transformation temperatures [7]. In some situations, considering the impossibility of measuring the temperature using direct methods such as thermocouples, the use of indirect methods is necessary [8]. Thermography is the most applied and, in some cases, the only possible technique used to measure the temperature of SMA elements since it allows to remotely quantify temperature variations in both scientific and engineering applications [9,10]. The mechanical properties of SMA during cycling are strongly temperature dependent. In this work, some commercial Ni-Ti wire specimens with 500 μm diameter are subjected to thermomechanical cycling. Thereafter, the changes in their thermodynamic properties, such as the evolution of transformation temperatures, hysteresis loops, and the linear relationship between austenitic (As and Af) and martensitic (Ms and Mf) transformation temperatures and the applied stress of 150 MPa, are investigated. The temperature changes of the sample were measured by recording the infrared radiation emitted from the surface. One should focus mainly on samples with the help of converging lenses for the use of IR sensors. In this type of application where the sample is a thin wire, trying to focus the sensor on such a small sample is a challenging task. In order to find more reliable methods of temperature measurement, an infrared (IR) sensor is focused on the samples while they are cycled through the forward and reverse martensitic transformations, between 25 to about 120^{0}C.

Materials and Procedures

A 500 μm in diameter and length 100 mm commercial Ni-Ti (54 at. % Ni) actuator wire was used in the present study. The wire is manufactured by Saes Getters S.p.A. Smart Materials under the brand name SmartFlex®. The nominal chemical composition is 54% Ni by weight, and Af > 90^{0}C. Some typical properties of this material are shown in Table 1. The general properties of the SmartFlex® wire are presented by Fumagalli, et al. [11]. A peculiar feature of SmartFlex® shape memory alloy wires is it was specially made to be used as actuators. The actuator wire temperature was determined with the use of a sensitive optical system equipped with an infrared (IR) sensor CTM-3SF22 (Micro-Epsilon) for non-contact temperature measurements. In order to find more reliable methods of measuring temperature, the IR sensor is focused on the sample while they are cycled through the forward and reverse martensitic transformations, between 25 to almost 120°C. The measurement temperature system used in the experiments is illustrated in Figure 1.

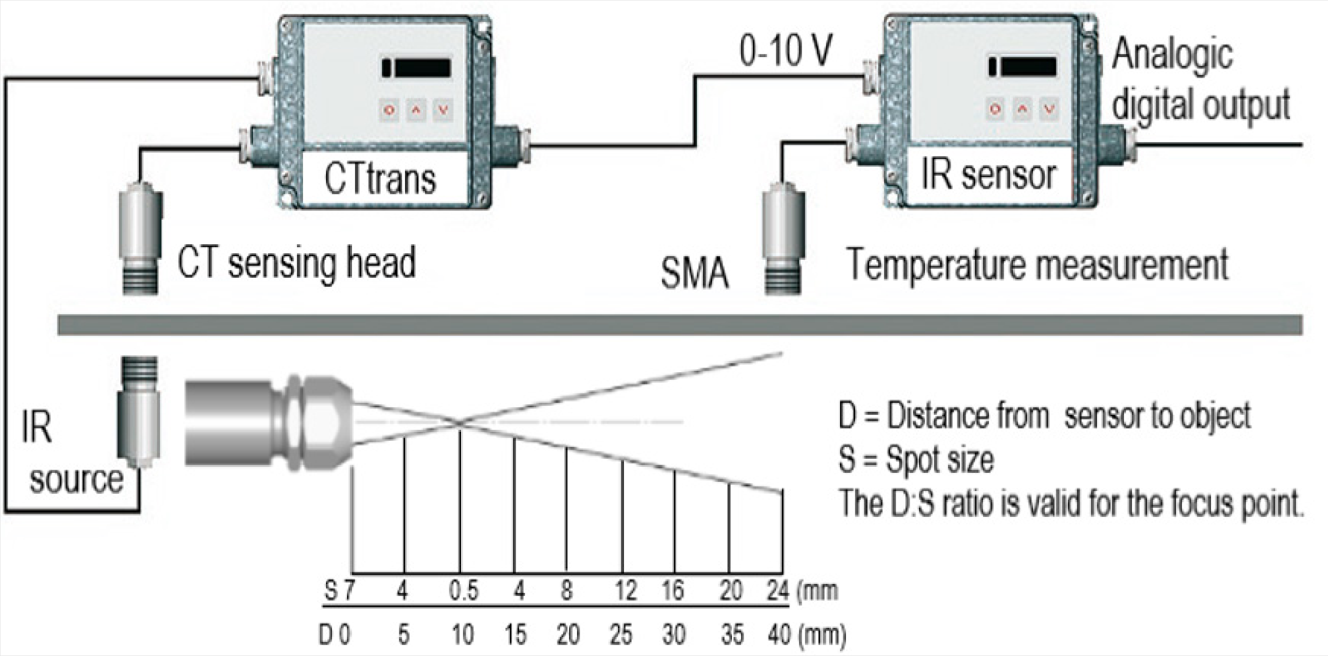

Figure 1: Scheme of measurements temperature system.

Measurement specifications of the sensor are: spectral range of 2.3 µm, temperature range - 40...125°C, temperature resolution (digital) 0.1°C, optical resolution 22:1, system accuracy ± (0.3 % of reading +2°C), exposure time 1 ms with dynamic adaptation at low signal levels, closed focus (CF) lenses and emissivity detection and correction. The CF lens allows the measurement of very small objects. To measure total hemispheric emissivity, the apparatus uses an active source and an IR detector connected to the controlling block through optical fiber cables, as shown in Figure 1. The total hemispheric emissivity of the wire sample was determined (integrated at 180°, in the range θ =-90° to θ =90°. If the emissivity of the material changes, the new emissivity is determined by the system and transferred via the 0-10 V output to the connected IR sensor for temperature measurement. The detailed description of the equipment shown in Figure 1 is presented by Da Silva, et al. [12]. In order to evaluate the results obtained from the developed device, a typical differential scanning calorimeter (DSC 8500 model, market by PerkinElmer®) was used to estimate the latent heat and phase transformation temperatures of the material when no stress is applied. DSC measurements were performed on the as-received material using a standard heating/cooling rate of 10°C min−1 and a thermal cycle between - 10°C and 110°C. The tangent method was used to determine the onset and endset transformation temperatures for the peaks per ASTM F2004-05 [13]. The wire temperature and strain values are correlated in hysteresis loops to estimate the phase transformation temperatures with the tangents of the curve.

Experimental Setup

The experimental thermomechanical cycling equipment was designed based on the custom test machine presented by Mammano and Dragoni [14] and reported by Da Silva, et al. [15]. Infrared (IR) temperature measurement sensors were added to the equipment. The upper part of the frame (C-shaped aluminium chassis) holds the main load cell to which one end of the wire under test is attached through a rigid clamp. The lower end of the SMA wire is loaded a mechanical with a stress of 150 MPa. The heating (actuation) of the wire is provided by Joule Effect produced by an electric current. Pulse width modulation (PWM) was used to control the current supplied through an electronic power board. The heating rate can be controlled indirectly by changing the waveform intensity of the supply current. Transformation temperatures are of course fundamental parameters to know and to control the actuation of wire by Joule Effect [11]. The generated pulses have the shape of a square wave with which is proportional to the activation time, as indicated in the schematic representation of Figure 2. To calculate the modulation, two parameters are used: the wave period and the pulse width, known as duty-cycle. The duty-cycle for the square wave was defined in percentage according to equation (1).

$$Duty\ Cycle = \frac{tON}{t} \ldots\ldots\ldots\ldots(1)$$

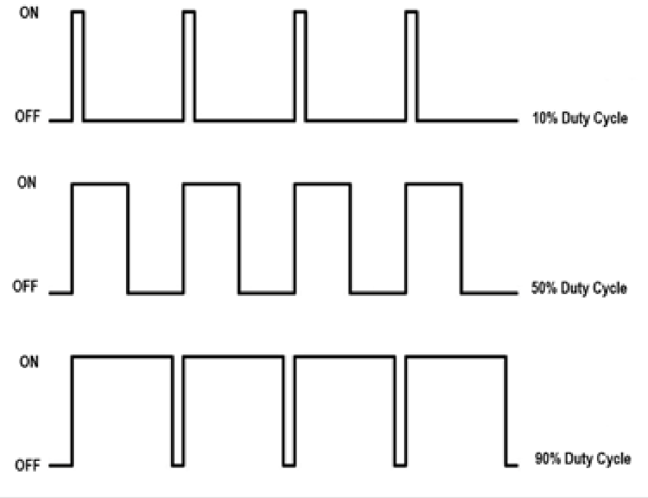

Figure 2: Square current waveforms.

Where ON is the time at which the signal remains on, and t is the wave period (time per cycle). The test parameters are set, controlled, and monitored by means of a Personal Computer (PC) which got a graphical interface of LabView® and the data are stored continuously on a hard disk drive (HDD). The program controls the (National Instruments USB 6251 DAQ board) hardware and receives the signals from temperature, force, and displacement sensors (IME30- 20NPSZC0K). The temperature is measured using the IR sensor positioned at a distance of 10 mm from the sample and the data acquisitions were done every 100 milliseconds. To prevent measuring errors, the object should fill out the field of view of the optics completely. Consequently, the spot size should at all times have at least the same size as the object or should be smaller than that. Once this setup was completed, a thermal cycle was performed. The 1–2°C margin of error in the temperature values should be taken into account in the results.

Results and Discussion

Figure 3 shows the phase transformation temperatures and the latent heat of transformations as functions of thermal cycles of the material when no stress is applied (σ =0). Figure 4 shows the change in hysteresis loops in the early cycles (strain vs temperature plot during cycling under the constant stress of 150 MPa). According to transition temperatures, the material must have a quasiplastic behavior at room temperature (approximately 25°C) and pseudoelastic above 87°C. If it is strained almost below 38°C and then heated above 87°C, it is expected to observe the shape memory effect (SME). In thermal cycling, these samples undergo an R-phase transformation instead of an austenitic–martensitic transformation until some specific number of cycles. This R-phase transformation restrains the plastic deformation and then generates smaller plastic strain values for these wires [16]. Some important information can be observed, such as the maximum stroke and the transition temperatures. The maximum stroke of the wire is around 5.5%, Mf at 41.4°C, and Af at 56°C. The maximum recoverable strain for SMA wire actuators (SmartFlex®) reaches 5% [11].

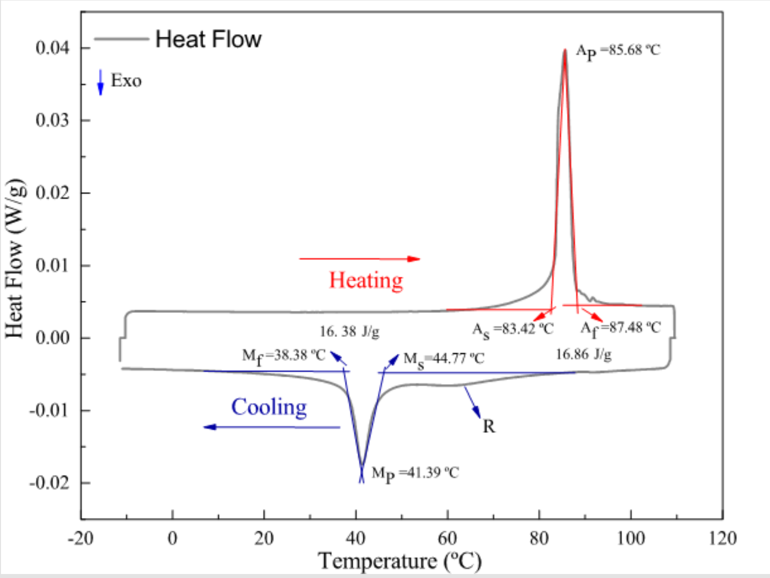

Figure 3: DSC curves of the Ni-Ti SmartFlex® wire.

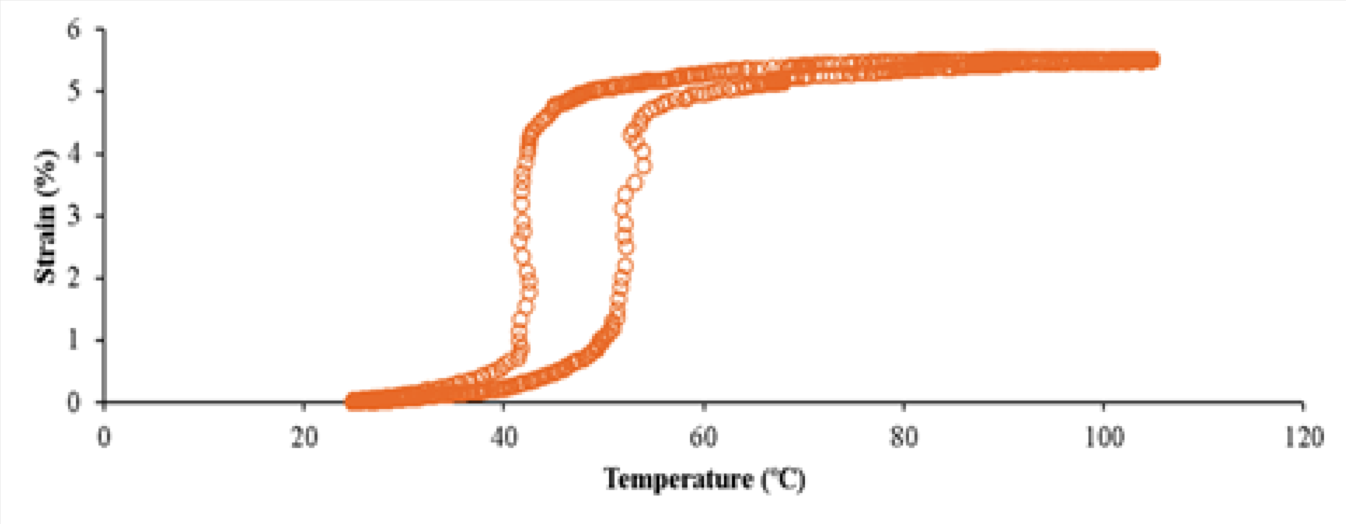

Figure 4: Hysteresis loop of a Ni-Ti alloy subject to thermal cycles and 150 MPa stress.

The phase transformation temperatures experimental obtained are summarized in Table 2 (σ =0 and σ =150 MPa). Figure 5 shows the influence of stress on the phase transformation temperatures. As can be observed, the phase transformation temperatures are different in all cases (Table 1). The difference observed between the transformation temperatures was caused by the applied load [1] and also, is justified, in part, by the changes that occur in the microstructure due to thermomechanical cycling [6,9]. Actuator wire temperatures are important parameters to measurement and control, in the case of wire actuated by the Joule effect. It could be observed that the transition temperatures change linearly with the applied load. The effect of the load level used is detected in the elongation rates: the higher the load level, the higher is also the elongation rate [16]. The Clausius–Clapeyron relationship is usually used to evaluate this effect. In figure, Fumagalli et al. [11] find an inclination of for NiTi SmartFlex® material against a value of 8.3 MPa/°C in the present work. The temperature measurement done by using the IR sensor presented the average absolute error of ± 1.5%.

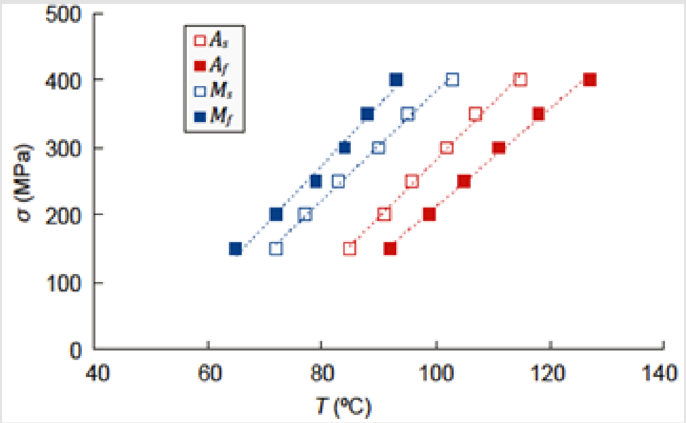

Figure 5: Influence of stress on phase transition temperatures.

Table 1: Characteristics of SmartFlex® actuator wire.

Product	Maximum Force [N]	Maximum Stroke [%]	Suggesting Force [N]
SmartFlex®	6.2/118	5.5	2.7/33
Hysteresis test @200MPa, 1 °C/minute			
As	86 °C		
Af	94 °C		
Ms	65 °C		
Mf	57 °C		
Fatigue behavior @3.5%	170 MPa 0.6A		
Number of cycles	>105		
Length drift	0.17%		

Note: Courtesy of SAES Getters S.p.A.

Table 2: Phase trasformation tempearatures data of SmartFlex®150.

SmartFlex®	Phase transformation temperatures				Hysteresis
	Mf (°C)	Ms (°C)	As (°C)	Af (°C)	(Ap - Mp) (°C)
Hysteresis test @150MPa	41.40±1	44.58±1	49.70±1	55.80±1	-
DSC test	38.38 ±1	41.39±1	83.42±1	87.48±1	44.29

Conclusion

The transformation temperatures and hysteresis loops were experimentally analyzed using a sensitive optical system equipped with an IR sensor to measure temperature. For the temperature range analyzed, the data reveal that the sensors can be used to estimate the temperature of thin SMA actuators (≤ 500 micrometers), despite their difficulty in focus. More samples should be analyzed to verify the evolution of the transformation temperatures of Shape Memory Alloy actuator wires subjected to thermal cycling. Based on the results presented in this paper, the measurement made using the infrared sensor showed an average absolute error of ± 1%. However, any disturbance of movement between the infrared sensor and the sample results in oscillation in the hysteresis plots of the loop.

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