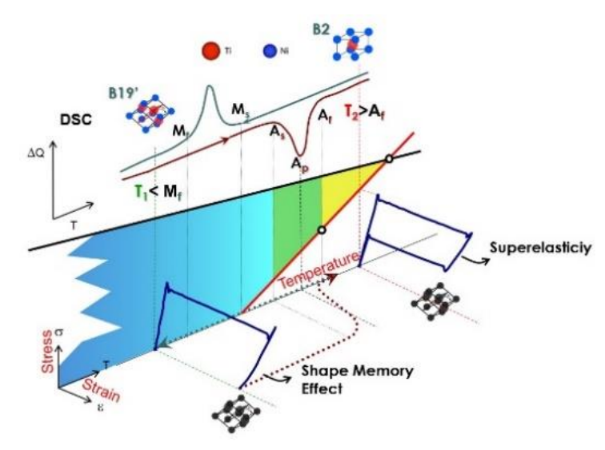
Modeling functional gradient in shape memory alloy wires



Workshop on Shape Memory Alloys
Processing, Properties and Applications
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ABSTRACT

Shape memory alloys (SMA) present interesting functional characteristics (shape memory effect and superelasticity) that make them quite attractive for a wide range of applications. These functional characteristics are a consequence of phase transformations that take place within well-defined temperature or stress ranges, depending on being thermal- or stress-induced. These temperature/stress ranges are functions of chemical composition and heat treatment of the material. For applications requiring a wider controllable range, a wider temperature/stress range than that associated to a specific composition/heat treatment may be required. In such a situation, the possible solution will be to use a functionally graded material.

The purpose of this work is to provide a basic design methodology for functionally graded shape memory alloy wires. The evolution of the wires subjected to load and temperature changes is simulated by integrating a simple system of ordinary differential equations through standard numerical routines.

To describe the constitutive behavior of SMA cables, we choose the Tanaka–Voigt model since it can easily be implemented and adjusted to a wide set of experimental data. A benchmark of our procedure is presented on a three-element system simulating a functionally graded SMA wires.

We consider only SMA elements with superelastic behavior, i.e. they are in austenitic phase at ambient temperature. Furthermore, we assume that martensitic phase transformations induce negligible temperature changes in SMA elements, because of the limited strain rates associated with small nodal velocities.

METHOD

EXPERIMENTAL

Samples have been cut with 55 mm length and the localized heat treatment (350 ºC for 10 minutes, Figure 1-a) has been carried out along a 32 mm long segment centered into the 55 mm long wire (Figure 1-b). Inside this 32 mm long segment subjected to localized heat treatment, two segments of 8 mm length (hereafter referred to as external, where a greater temperature gradient exists) have been separated from a central part 16 mm long (hereafter referred to as internal, where the temperature is practically uniform).

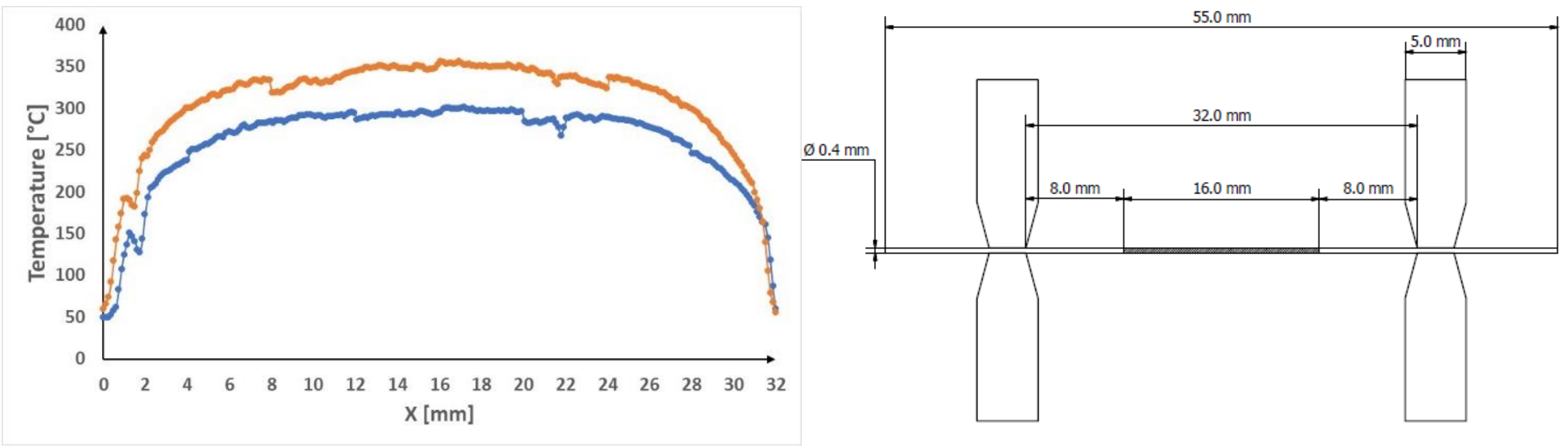

Figure 1 – Localized heat treatment of the NiTi wires:
(a) Measured temperature profile for the heat treatments at 300, 350 ºC (at the central region).
(b) Subdivision of the wire in internal and external segments (see the text).

The tensile tests were performed in a Shimadzu NG50KN, using a 500 N load cell. All tests consisted of 3 cycles, run with a cross-head speed of 1 mm/min and maximum stroke of 6% of the gauge length. For each sample, two different gauge lengths have been tested:
(i) 32 mm gauge length, where the tensile test is representative of the total length of the localized heat treatment;
(ii) 44 mm gauge length, where the tensile test is representative of the "composite" behavior of the heat treated segment (32 mm long) and two segments 6 mm long at each extremity that did not suffer the direct heating by Joule effect.

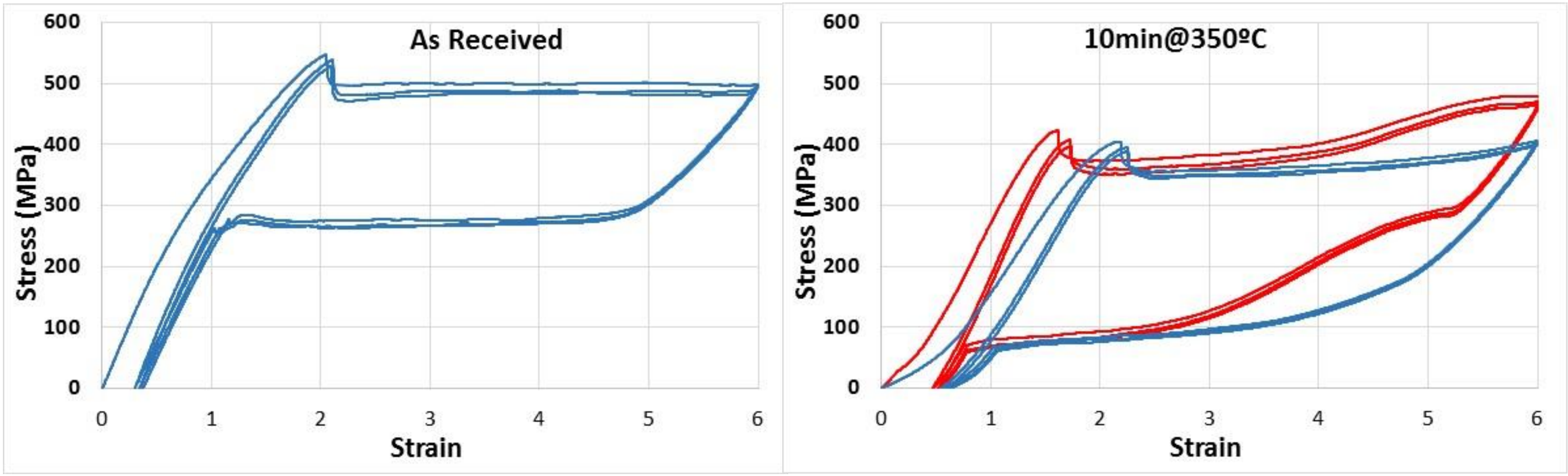

Figure 2 – Tensile tests of samples (a) as-received wire; (b) @350ºC different conditions of heat treatment: 32 mm gauge length (blue – local heat treated) and 44 mm gauge length (red - local heat treated + non-heat treated edges)

Below are two tables highlighting the sample properties and key stress points.

Table 1 - Transformation temperatures for localized heat treatment at 350 °C, for 10 min
Mechanical characteristics as a function of the heat treatment for the 32 mm gauge length (local heat treated) and 44 mm gauge length (local heat treated + non-heat treated edges): (a) Peak value of the stress-induced martensite; (b) Stress value for the lower plateau (2.5% strain) and higher plateau (5.5% strain).

	Time (min)	Rs (°C)	Rp (°C)	Rf (°C)	Ms (°C)	As (°C)	Af (°C)
Int	10	30.4	23.2	5.2	-55.0	-11.6	34.3
Ext	10	37.3	23.9	12.6	-43.5	-10.5	38.1

		Strain	
	Peak SIM	2.5%	5.50%
Stress (MPa)	423	376	474

SIMULATION

To perform the simulation, a Tanaka-Voigt model was chosen; two sets of super elastic cables were used, an outer and an inner (Figure 3), and all load, temperature and phase changes were calculated using a system of ordinary differential equations written in matrix form, solved using standard numerical routines.

Figure 3 – Linear design. Blue – Inner; Red – Outer

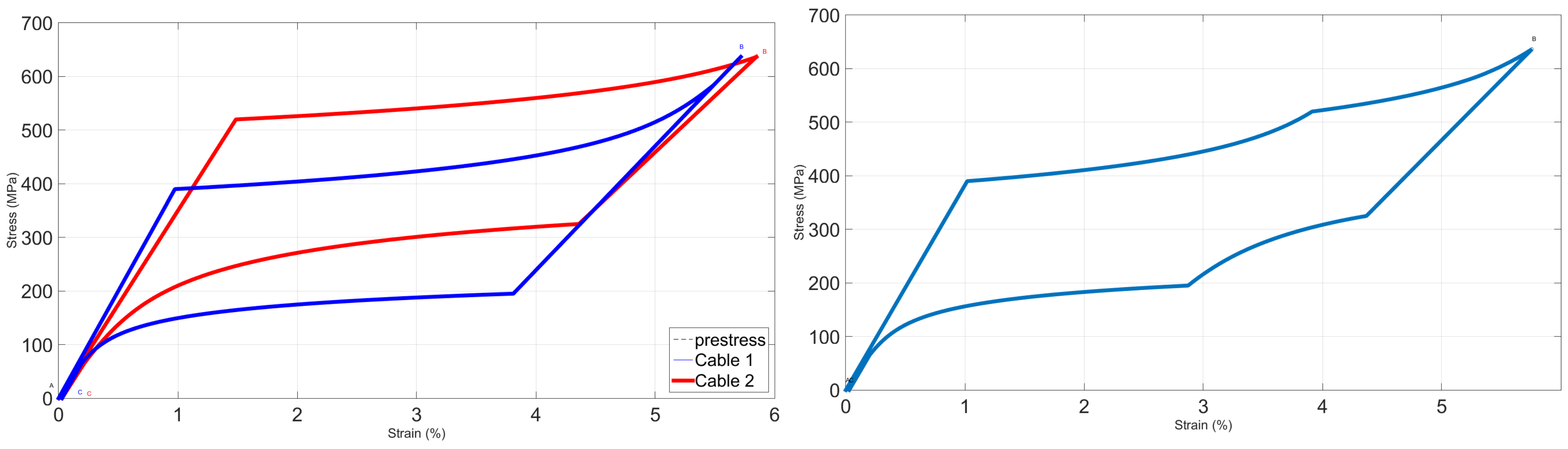

Figure 4 – SMA simulations: (a) Subdivision of the wires in internal and external segments. (b) Simulation result for the final "composite" SMA (see text).

Table 2 – Properties used in the simulation:

	As (ºC)	Af (ºC)	Ms (ºC)	Mf (ºC)	Ea (GPa)	Em (GPa)	T (ºC)	Diameter (mm)
Inner	-30	10	-60	-90	35	20	20	0.4
Outer	-10	10	-40	-70	40	23	20	

Data	
CA=CM	6.5 MPa/ºC
E (Austenite)	80 GPa
E (Martensite)	25 GPa
Maximum Strain	7.5%

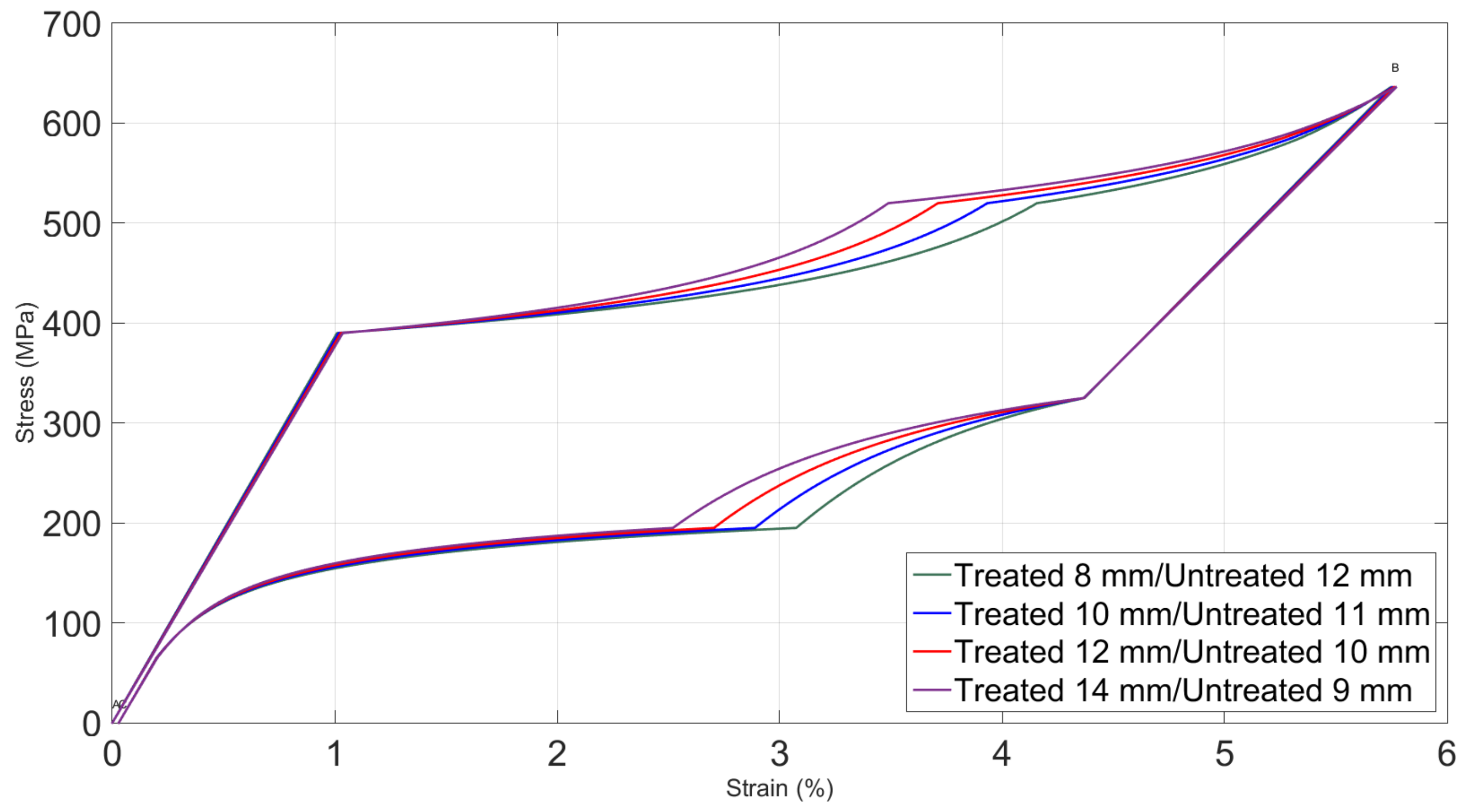

Figure 5 – SMA simulations. Treated sections are the inner and untreated sections are the outer portions of the wire simulation.

CONCLUSIONS

With this work we were able to produce a model capable of predicting functionally graded SMA behavior during a tensile test for a given temperature and localized heat treatment. This model will help us to make an estimate of the relative fraction of the different regions resulting from localized heat treatments.

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