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# Active shape change of an SMA hybrid composite plate

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**Abstract.** An experimental study was carried out to investigate the shape control of plates via embedded shape memory alloy (SMA) wires. An extensive body of literature proposes the use of SMA wires to actively modify the shape or stiffness of a structure; in most cases, however, the study focuses on modeling and little experimental data is available. In this work, a simple proof of concept specimen was built by attaching four prestrained SMA wires to one side of a carbon fiber laminate plate strip. The specimen was clamped at one end and tested in an environmental chamber, measuring the tip displacement and the SMA temperature. At heating, actuation of the SMA wires bends the plate; at cooling deformation is partially recovered. The specimen was actuated a few times between two fixed temperatures $T_c$ and $T_h$, whereas in the last actuation a temperature $T_f > T_h$ was reached. Contrary to most model predictions, in the first actuation the transformation temperatures are significantly higher than in the following cycles, which are stable. Moreover, if the temperature $T_h$ is exceeded, two separate actuations occur during heating: the first follows the path of the stable cycles; the second, starting at $T_h$, is similar to the first cycle. An interpretation of the phenomenon is given using some differential scanning calorimeter (DSC) measurements. The observed behavior emphasizes the need to build a more comprehensive constitutive model able to include these effects.

**Keywords:** shape memory alloy; composite plates; active shape change.

## 1. Introduction

In the last decades, the development of various classes of active materials has paved the way to numerous applications in many engineering fields. In particular, an important area of research is that of active composites, in which an active material is embedded in a structure thus bestowing active properties on the structure itself.

Shape memory alloys (SMA) are a particular class of active metals whose behavior is strongly influenced by stress and temperature. Thanks to a solid-solid reversible phase transformation, these materials are able to recover their original shape when heated above a set temperature. If the material is not allowed to recover its shape completely, it develops a recovery stress which can be used for actuation.

The idea of embedding SMA wires or ribbons in structures to create shape memory alloy hybrid composites (SMAHC) dates back to the 1990s. The shape recovery and stress generation capabilities of SMA can be used to control the buckling (Baz, *et al*. 1992, Lee and Lee 2000), vibration (Żak, *et al.*

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2003, Aoki and Shimamoto 2003) and shape (Turner, *et al.* 2004, Gao, *et al.* 2006) of a structure. A lot of attention has been focused on plate and shell type structures because of the many possible applications in mechanical and aerospace engineering and, recently, also in civil engineering (actuators, morphing airplane wings for improved aerodynamics, control of panel flutter etc).

The potential of active control via SMA wires has been widely demonstrated, however many issues still need to be tackled. In shape control, reliability and repeatability of the actuation are crucial and need to be investigated experimentally. According to simulations based on SMA phenomenological constitutive models (Daghia, *et al*. 2006, 2008), the actuation starts at the transformation temperature and the amount of displacement which can be obtained is strictly connected to the recovery stress. These two parameters depend in turn upon the loading history and current stress and temperature conditions of the SMA, which unfortunately cannot be fully controlled when dealing with a composite. Indeed, the behavior of the composite arises from the interaction between the different materials of which it is made and, thus, is in general more complex than the behavior of the singular constituent. Moreover, in SMAHC it is not possible to fully exploit the shape memory effect, which allows to erase the loading history of the material by heating it above a certain temperature at zero stress, thus the full loading history must be taken into account.

This work presents a study to demonstrate the feasibility of shape control of plates via SMA wires. A specimen was built by gluing four prestrained SMA wires to a carbon fiber laminated plate strip. Actuation of the wires was carried out in an environmental chamber in order to control both heating and cooling of the SMA. The specimen was actuated a few times between two fixed temperatures $T_c$ and $T_h$, in order to test the repeatability of the actuation, whereas in the last actuation a temperature $T_f>T_h$ was reached to investigate the effect of a change in the actuation conditions.

The experimental results show an unexpected difference between the first actuation and the following cycles, which are stable. Moreover, if the maximum temperature reached in the first cycle is exceeded, the actuation path changes significantly. These phenomena are preliminarily investigated by doing some calorimetric measurements and an explanation is proposed. This experimental results emphasize the need for a more thorough understanding of the SMA behavior and testing of the composites.

The paper is organized as follows. The design and building of the specimen is described in Section 2. Section 3 presents the experimental setup and results. An explanation for the unexpected behavior observed is proposed in Section 4.

## 2. Composite design and building

In this section, a simple specimen to demonstrate the shape control capabilities of embedded SMA wires is designed and built.

The concept of shape control is based on the reversible austenite/martensite phase transformation which takes place in shape memory alloys. Austenite is a high symmetry phase, stable at high temperatures and low stress levels, whereas martensite is a low symmetry phase which can be generated by cooling or by stressing. A temperature change at zero stress generates twinned martensite, which is macroscopically analogous to austenite, whereas the presence of stress establishes a preferred orientation for the crystals, thus generating detwinned martensite, associated to a macroscopic shape change. In the following, the term martensite refers to detwinned martensite unless otherwise specified. This is because from the macroscopic point of view there is no interest in distinguishing between austenite and twinned martensite.

The transformation temperatures are physical properties and, at zero stress, are indicated by $M_f < M_s < A_s < A_f$, where $M$ denotes the $A \rightarrow M$ transformation, $A$ denotes the $M \rightarrow A$ transformation, the subscripts $s$ and $f$ stand for the temperatures at which the transformation starts and finishes, respectively. The transformation temperatures increase almost linearly as the stress increases.

Shape control can be achieved by embedding prestrained SMA wires inside a host structure in particular locations, which depend upon the final shape to be achieved. The prestrain generates a certain amount of martensite, which tends to transform back into austenite as soon as the transformation temperature is reached. Because of the presence of the host structure, the SMA is not allowed to fully recover its original shape, thus a recovery stress is generated which in turn modifies the shape of the host structure. At cooling, some of the austenite transforms back into martensite and the recovery stress relaxes, thus the structure moves back to its original configuration. Depending upon the temperatures reached during actuation and cooling, different levels of shape change can be achieved.

The design of a shape control structure requires first of all the definition of the target shape to be obtained during actuation. Bending can be induced in a plate by embedding SMA wires at a fixed distance from the plate midplane. The amount of deformation can be quantified, for example, by measuring the tip displacement of the plate in a cantilevered configuration.

In this study, a proof of concept specimen was built for bending shape control of plates. A carbon fiber laminated composite plate with SMA wires bonded to one of the external surfaces is considered in order to avoid the technological issues related to the building of the composite with embedded wires. These were beyond the aim of the present study and will be the subject of future work. The geometry of the specimen is designed to achieve a mostly one dimensional, beam-like actuation.

A schematic representation of the concept just described is shown in Fig. 1.

### 2.1. Host structure and SMA wires characteristics

The host structure is a symmetric cross-ply laminate plate of thickness 1.5875 mm from McMaster-Carr (www.mcmaster.com). Plate strips of 203.2×25.4 mm (8×1 in) were cut from the original square plate. The plate properties were characterized via static testing (bending and tensile tests on specimens taken in both laminate directions).

A Nitinol wire spool of 0.38 mm diameter was provided by Fort Wayne Metals Research Products Corp. The material properties of the Nitinol were determined via differential scanning calorimeter (DSC) tests and tensile tests at different temperatures. The DSC tests were used to determine the phase transition temperatures $M_f$, $M_s$, $A_s$ and $A_f$, which turned out to be 0°, 27°, 40° and 55° Celsius, respectively. This means that the actuation should begin at 40°, and that upon cooling down at ambient temperature a certain amount of residual deformation should be present. The SMA material properties were evaluated through tensile tests carried out inside a Tenney vacuum-temperature chamber (model 36ST).

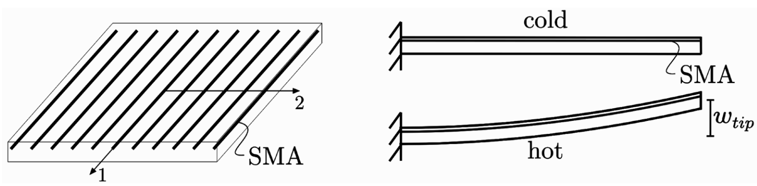


Fig. 1 Bending shape control of plates with embedded SMA wires

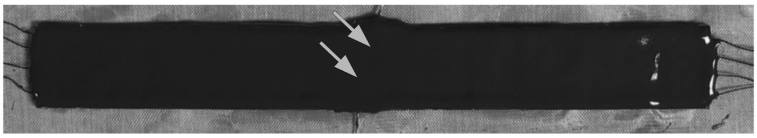

Fig. 2 SMAHC specimen

The data obtained in the material characterization, reported in Appendix A, was used in a finite element simulation (Daghia, *et al.* 2006, 2008) in order to predict the shape control capability of the final specimen. In the FEM analysis, the SMA behavior was modeled using the well-established Brinson constitutive model (Brinson 1993). The results show stable cycles in the displacement/temperature plane and a certain amount of residual deformation after cooling to ambient temperature.

### 2.2. Specimen preparation

The specimen preparation requires two steps. First of all, the SMA wires must be prestrained at room temperature by a certain amount, usually 3-4%, then they must be bonded to the host structure.

The actuation capabilities of the SMA wires depend essentially on the prestrain, thus this is a critical phase in the specimen building. All the wires should be prestrained by the same amount and no residual internal stresses and other deformations apart from those given during the prestrain should be present. In order to ensure this, the wires were heated with a Craftsman industrial heat gun before prestraining. Two 550 mm long SMA wires were prestrained contemporarily, using an Instron 4204 machine. Each wire was then cut into half to obtain four equally prestrained wires.

The bonding of the SMA wires to the host structure is an equally important phase upon which the final result in terms of actuation depends. The wires should be straight, evenly spaced and laid out symmetrically with respect to the beam axis of symmetry in order to avoid undesired torsional deformation during actuation. The adhesive should be compliant in order to modify as little as possible the stiffness properties of the original laminate. Moreover, it should cure at room temperature in order to avoid actuation of the SMA wires, so that no constraint is required to maintain the wires prestrain during adhesive curing. All the stated reasons let to the choice of 3M Scotch-Weld 2216 B/A Epoxy to create the bonding layer. Two layers were applied, each was left to cure for 24 hours at room temperature.

Two Omega type J thermocouples (model 5TC-TT-J-36-36) were attached to two of the wires at approximately half the beam length with conductive tape before bonding the SMA to the laminate. This allowed to acquire wire temperature data during the experiments. Fig. 2 shows a picture of the specimen, the thermocouples' positions are marked with arrows.

## 3. Experimental testing

### 3.1. Setup

The specimen was tested in the environmental chamber in order to control both heating and cooling. In real life applications, SMA actuators are usually heated via resistive heating. This technique allows to heat the SMA quickly and achieve rapidly the final configuration, while little control is possible on the cooling. For experimental purposes, on the other hand, a relatively slow and controlled heating and

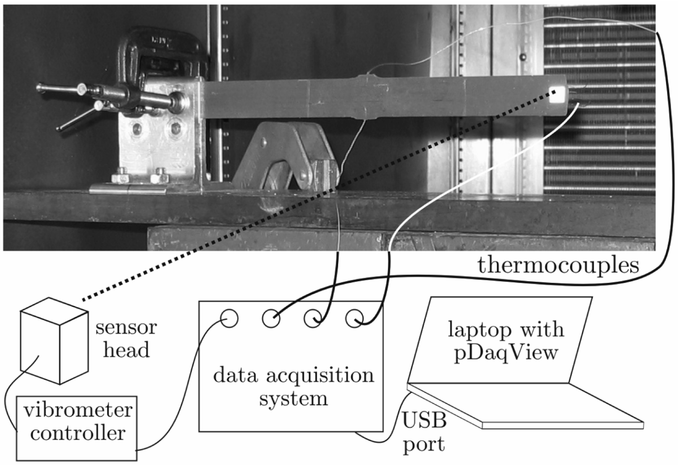


Fig. 3 Schematic experimental layout

cooling was required.

The SMAHC was clamped at one end, leaving a free length of 168 mm. Reflective tape was attached at the free end of the beam and a Polytec laser vibrometer (OFV 303 Sensor head and OFV 3001 Vibrometer controller) was used to measure the tip displacement. Temperature readings were obtained from two embedded thermocouples and from another thermocouple of the same type, attached to the wire just outside the epoxy layer. In this way the temperature difference along the SMA wires was captured: the wire ends, in direct contact with the air inside the chamber, heat up and cool down more quickly than the parts embedded in the epoxy.

The thermocouples and the laser vibrometer were connected to a USB data acquisition system by Omega (model OMB-DAQ-56). The temperature and displacement readings were recorded on a laptop equipped with the pDaqView software.

Starting from ambient temperature, the air in the chamber was slowly heated up to $T_h = 125$ °C and then slowly cooled down to $T_c = 20$ °C. The sequence was repeated several times in order to obtain various actuation cycles. In the last cycle, the final temperature during heating was $T_f = 137$ °C $> T_h$. A schematic representation of the experimental setup is reported in Fig. 3.

### 3.2. Results

The specimen behavior is characterized in terms of displacement vs temperature graphs. These are shown in Figs. 4 to 6. The temperature considered is the one measured by the external thermocouple.

The first actuation is shown in Fig. 4. The graph starts from point A and follows the direction of the arrows. Upon heating the displacement increases, first slowly due to a different coefficient of thermal expansion between the wires and the laminate, then more quickly as the phase transformation starts. At 125°C the tip displacement is 12.4 mm. Upon cooling, the displacement decreases again thanks to the $A \rightarrow M$ phase transformation. However, a residual tip displacement is present when the specimen reaches room temperature.

Fig. 5 shows again the first actuation (black line) and two representative examples of the following cycles between $T_c$ and $T_h$ (starting from points B and C, respectively). Between the different loading

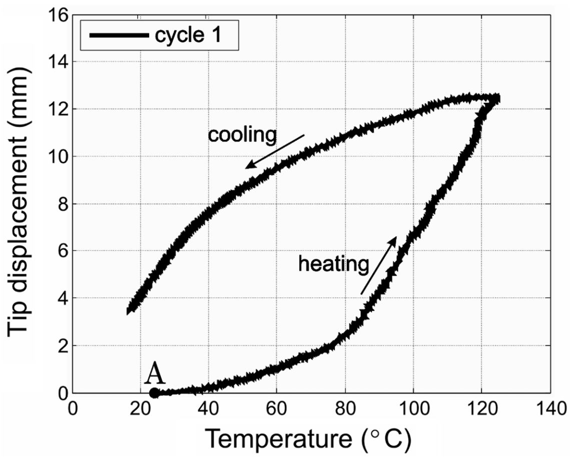


Fig. 4 Temperature vs tip displacement (cycle 1)

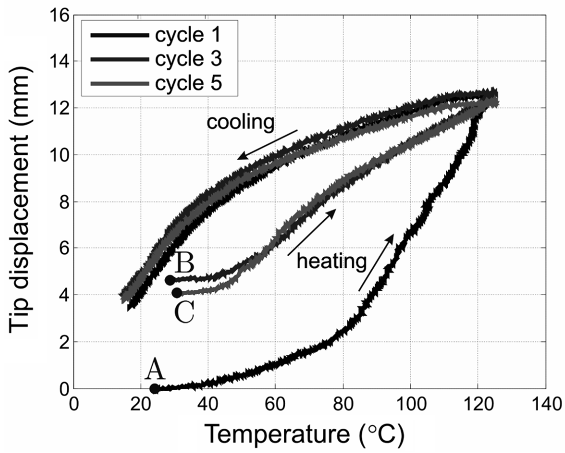


Fig. 5 Temperature vs tip displacement (cycles 1, 3 and 5)

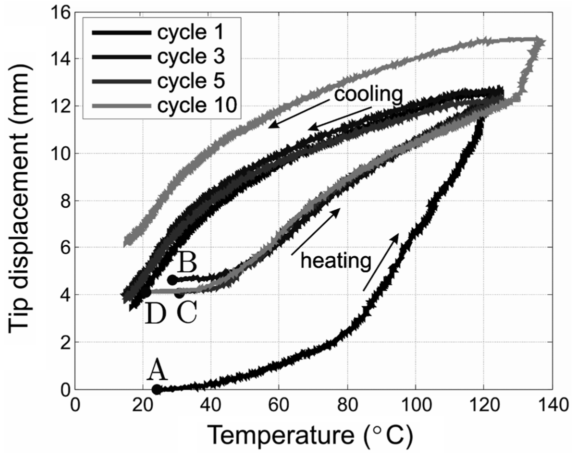


Fig. 6 Temperature vs tip displacement (cycles 1, 3, 5 and 10)

cycles, the environmental chamber was opened in order to check the equipment and the specimen, therefore there is a little temperature gap when data was not recorded.

As it can be noted in the graphs, the heating branch of the first cycle is quite different from that of the following cycles, which are stable. In particular, the first actuation occurs at higher temperatures. This difference was unexpected, since according to the preliminary simulations (Daghia, *et al*. 2006, 2008) the path followed by the different actuations should be the same.

In order to further investigate this peculiarity, another actuation cycle was carried out in which the final temperature inside the chamber was $T_f = 137$ ºC > $T_h$. This cycle is shown in Fig. 6 (light grey line, starting from point D) along with the previous cycles.

Two different steps in the actuation can be observed in the last cycle. The first, following the path of the stabilized cycles, occurs at temperatures $T < T_h$, whereas the second starts at $T_h$ and continues along the path marked by the first cycle. Again, this behavior is unexpected because it is not predicted by the preliminary simulations.

## 4. Interpretation

The differences between the loading cycles presented in the previous section could be explained by admitting the presence in the SMA wires of different types of detwinned martensite, characterized by different transformation temperatures. Indeed, detwinned martensite can be generated by an applied stress at constant temperature ($M^s$) or by cooling in the presence of a non zero stress ($M^t$). Most phenomenological models do not distinguish between the two situations, thus no difference was expected in the transformation temperatures. However, admitting that $M^s$ has higher transformation temperatures than $M^t$ leads to a possible explanation of the experimental results.

Let us consider in particular the first and last cycles. Before the first actuation, $M^s$ type martensite is present in the SMA wires because of the prestraining, thus in the first cycle actuation occurs at higher temperatures than those expected from the preliminary calorimetric measurements (see Section 2). In the first thermal cycle, some $M^t$ is generated during cooling in the presence of an applied stress. Thus, in the following cycles a two step actuation is possible: $M^t$ transforms at lower temperatures, while, if the temperature reached in the first cycle is exceeded, $M^s$ comes into play again and transforms along its original path. This is the behavior observed in the last cycle.

In order to verify this hypothesis, some differential scanning calorimeter (DSC) tests have been carried out at the Chemistry Department of the University of Bologna. Three different specimens were considered, each with a different loading history. The first specimen has been heated above $A_f$ and cooled at zero stress in order to erase the previous loading history, thus it behaves like a 'virgin specimen'. The second has been prestrained by 4%, thus it represents the wire situation before the first actuation, while the third has been prestrained and then electrically heated while keeping the deformation constant, thus simulating the conditions of the wires inside the composite after the first actuation cycle. The thermal cycle at constant deformation (constrained recovery) is an approximation of the actual loading history of the wires embedded in the composite. Actually, constant deformation should be interpreted as a limit condition, since the wires recover some of their original prestrain due to matrix compliance. All this said, it is clear that the DSC specimens reproduce approximately the actual loading history of the wires embedded in the composite, thus the following results should be intended as a qualitative explanation of the phenomenon observed in the composite.

The DSC tests on the three specimen described permit to evaluate the transformation temperatures at zero stress for the different loading histories. The results are shown in Fig. 7, where a trough indicates $M \rightarrow A$ phase transformation. Only the first heating is shown since it is the only relevant part. Indeed, after the end of the $M \rightarrow A$ transformation the previous loading history of the material is erased.

As it can be noted, the transformation temperatures at zero stress for the three specimens are far from being the same. In the first specimen, the temperatures are those determined in the material characterization. In the second specimen, the trough has narrowed and shifted significantly to the right, thus showing an increase in the transformation temperatures. In the third specimen, finally, the trough is much wider and two different peaks can be noted.

These results appear to be in agreement with the interpretation given to explain the composite actuation cycles. In the second specimen the martensite was generated by stress ($M^s$) and the transformation temperatures are higher than for the first specimen. In the third specimen, part of the martensite was generated during the thermal cycles by cooling at non zero stress ($M^t$), thus a wider transformation region with two different peaks is observed. It should be underlined that the transformation temperatures obtained via DSC tests are not the same as the actuation temperatures observed in the SMAHC, as the latter are also influenced by the stress present in the SMA wires.

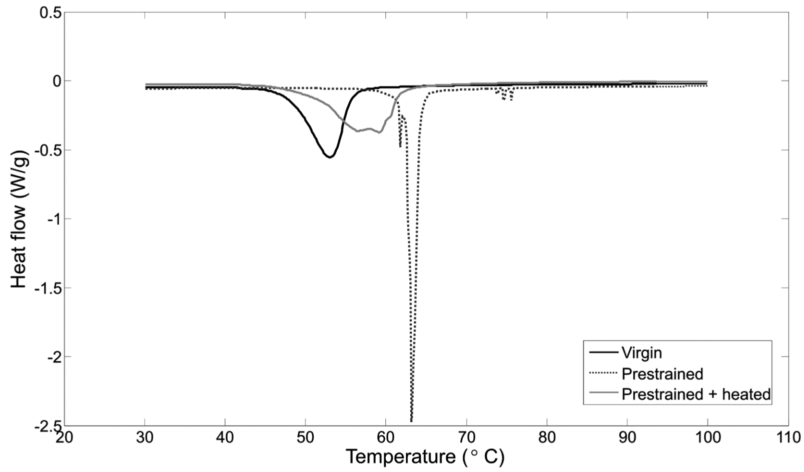


Fig. 7 DSC tests

However, the temperature shift observed between the SMAHC curves in the different actuation cycles is similar to the one recorded in the DSC measurements.

A similar result was reported in (Li, *et al.* 2003) while considering SMA wires in constrained recovery. Indeed, the increase of the transformation temperature of martensite because of prestrain is a known phenomenon (Liu and Favier 2000; Liu 2004), however it has not yet been explained and investigated thoroughly and to the authors' knowledge is still not included in the constitutive models available in the literature. Recently some attempts have been made towards this direction by introducing different transformation temperatures for the twinned and detwinned martensite (Popov 2005; Popov and Lagoudas), however this is not sufficient to account for the phenomena observed in these experiments, which deal exclusively with detwinned martensite.

## 5. Conclusions

A proof of concept specimen for the shape control of plates via embedded SMA wires has been built and tested. While confirming the basic concept behind SMAHC, the experiments emphasized some important differences between the actuation cycles. Some DSC tests introduced a preliminary interpretation of the phenomenon.

The results presented emphasize some key issues which must be considered when designing and building a composite with embedded SMA wires. On the experimental side, it is necessary to stabilize the actuation before embedding the SMA wires into the matrix, by doing some thermal cycles at fixed deformation up to the maximum actuation temperature, which should never be exceeded in exercise. On the modeling side, it is necessary to include the observed phenomena into the existing constitutive models in order to predict more accurately the response of the SMA wires, by taking into account the whole loading history.

Future experimental work on the topic of SMAHC includes the building and testing of an actual composite with embedded SMA wires and the investigation of the effect of training of the embedded SMA wires.

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## Appendix

The material properties of the carbon fiber laminate were determined via tensile and bending tests on specimens cut in the two principal material directions. The directions are defined as 1 and 2 in accordance with Fig. 1.

From the tensile tests, the following axial rigidities were evaluated:

$$A_1^r = 981 \text{ kN} \quad A_2^r = 1045 \text{ kN}$$

while from the bending tests the following flexural rigidities were evaluated:

$$F_1^r = 2.11 \cdot 10^2 \text{ kNmm}^2 \quad F_2^r = 2.24 \cdot 10^2 \text{ kNmm}^2$$

Some post processing allowed to obtain the constitutive equations associated to the plate model, which were used in the numerical simulations (Daghia, *et al.* 2006, Daghia, *et al.* 2008).

The Nitinol wires were characterized by defining the properties associated to the Brinson constitutive model (Brinson 1993), which was adopted in the simulations. They are the following:

$$\begin{array}{r|r|r} M_f = 0^{\circ}\text{C} & E_M = 7\text{GPa} & \sigma_s = 90\text{MPa} \\ M_s = 27^{\circ}\text{C} & E_A = 28\text{GPa} & \sigma_f = 140\text{MPa} \\ A_s = 40^{\circ}\text{C} & C_M = 8\text{MPa}/^{\circ}\text{C} & \varepsilon_r = 0.065 \\ A_f = 55^{\circ}\text{C} & C_A = 8\text{MPa}/^{\circ}\text{C} & \end{array}$$

where $M_f$, $M_s$, $A_s$ and $A_f$ are the transformation temperatures previously defined, $E_M$ and $E_A$ are the martensite and austenite elastic moduli respectively, $C_M$ and $C_A$ are the stress influence coefficients in martensite and austenite respectively, $\sigma_s$ and $\sigma_f$ are the critical stresses of start and finish detwinning respectively and $\varepsilon_r$ is the maximum transformation strain.