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The Change in Resistance During the Reverse Transformation of a NiTi Shape Memory Alloy

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Abstract

Shape memory alloys have been used for actuation purposes because of their shape memory effect. However, for a lot of applications the functional degradation is a limiting factor that needs to be overcome. Others have proposed that partial transformations can mitigate functional degradation through which shape memory alloys become useful for more applications. However, controlling partial transformations poses challenges because parameters, such as transformation temperature and required transformation energy, shift during the life of the material.

Electrical resistance has a direct relation with the extent of transformation. Although this relation is not linear, it could still be used for control of partial transformation if the relation is understood well. Electrical resistance is dependent on the temperature, extent of transformation, and percolation. Percolation in turn depends on the transformation sequence. A local connected path of transformed material will lower the overall resistance of the material due to the lower electrical resistance of austenite. If a row of material transforms first, it will have a larger influence on resistance than randomly distributed transformations.

It is shown that the change in resistance can be understood when considering the temperature, extent of transformation, and percolation. The influence of percolation is present, but small. Therefore, the change in resistance mostly depends on the change in temperature and strain. This understanding of the change in resistance can then be used for accurate control of partial transformations undergoing repetitive cycles. The most important aspects which influence the accuracy of this method are also identified.

1. Introduction

The shape memory effect makes shape memory alloys (SMAs) very interesting for actuation purposes[10, 12]. The high energy density and large stroke makes these materials more suitable for flaps on airfoils than, for example, piezo-electric actuators[8]. A remaining challenge is the limited functional life of SMAs[1, 8]. It has been proposed that partial transformation cycles (PTCs) can mitigate a large part of created damage and thereby extend the functional life significantly[2, 10, 11].

PTCs can improve the functional life of SMAs because the most damaging part of the transformation is excluded from the actuation. The last part of the transformation needs the highest energy gradient and thus is the most damaging to the microstructure of the material[7, 11].

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However, the challenge with PTCs is controlling the extent of transformation. Most control parameters shift during the life of the material and are therefore not suited for control. In previous research, attempts were made for controlling PTCs using temperature[2], strain response[10], energy differential[11], and electrical resistance[5]. Of these parameters only electrical resistance has a direct link to the extent of transformation, because it mostly depends on the ratio of austenite and martensite in the material. Unfortunately, the change in electrical resistance is very non-linear during the transformation.

Full understanding of the non-linear behaviour of electrical resistance during the transformation of SMAs is important for control of actuation. Knowing the relation between transformation and resistance will allow for accurate steering of SMA actuators and also raises the possibility of studying the effects of partial transformations on functional degradation more accurately.

In this article a model is proposed that can replicate the change in resistance during the reverse transformation of an SMA. First, the model is explained and required material properties are given (section 2). Second, the model is compared to experimental data (section 3). Finally, a discussion of the correlation will be given, together with recommendations for future improvements (section 4).

2. Method

The electrical resistance of SMAs is dependent on the temperature, strain, and transformation. The temperature and strain dependence are material constants. Obtaining these constants is explained in section 2.1. The change in resistance due to the transformation depends on percolation. How percolation can be modeled is explained in section 2.2. In section 2.3, the method for obtaining experimental data is given.

2.1. Material Constants

The strain dependence of resistance of materials is non-linear. The change is dependent on the length of the specimen and the cross-sectional area[4]. Both of these parameters change during the test and are dependent on the transformation of the material and the poisson’s ratio. Therefore, the strain dependence of the resistance was determined by curve fitting a second degree polynomial to experimental data.

The strain dependence was quantified using a Zwick/Roell 20 kN static tensile/compressive bench. A wire (Saes-Getters, SmartFlex, material code 5S0007, 0.4 mm diameter) was suspended in the test bench and connected to a Delta Elektronika power supply (ES015-10) which was controlled using a Labview program (National Instruments). The wire was subjected to a load of 5 N, at this load the length of the wire was taken as the original length. The wire was then strained with steps of 1 % to a maximum of 3 % while resistance was monitored. These four readings (0 through 3), were plotted and the strain dependence of the material could be determined.

For SMAs material constants need to be determined for the martensitic phase as well as for the austenitic phase. For testing the material in the martensitic phase a current of 0.1 A was used. For testing the material in the austenitic phase a current of 2.2 A was used for both heating and resistance monitoring. The temperature was monitored using an IR camera. The calculation method for determining the strain dependence of both martensite and austenite is given in Table 1.

Most materials have an electrical resistance that is linear dependent on temperature[4]. The temperature dependence was determined using the same equipment in the same setup as mentioned above. However, for this experiment the current was increased from 0 to 2 A in 600 s, while the test bench was at a fixed displacement. The reason for a very slow increase of current was to have a near steady state situation at each measurement. Because heat and stress are two competing phenomena in terms of transformation in SMAs, a very slow heating rate will result in a more accurate and repeatable test.

The resistance was taken at every 10 ^{o}C increase and plotted at low temperatures (<60 ^{o}C) for martensite and at high temperatures (>130 ^{o}C) for austenite. The temperature coefficients of resistance for both martensite and austenite are given in Table 2.

Table 1: Calculation method used to determine the increase of resistance of the SMA as a result of strain.

Description	**Formula**
Strain dependence, martensite	$R = R_0(0.0018 \cdot \varepsilon^2 - 0.025 \cdot \varepsilon + 1.0229)$
Strain dependence, austenite	$R = R_0(0.0016 \cdot \varepsilon^2 - 0.0346 \cdot \varepsilon + 1.0325)$

Table 2: Temperature dependence of the SMA.

Parameter	**Description**	**Value**	**Unit**
α_M	Coefficient for temperature dependence, martensite	$1.377 \cdot 10^{-3}$	$[°C^{-1}]$
α_A	Coefficient for temperature dependence, austenite	$0.438 \cdot 10^{-3}$	$[°C^{-1}]$

2.2. Percolation

The percolation theory was originally developed as a purely mathematically exercise to calculate the critically required concentration of holes in a medium to have a connected path through that medium[3]. Kirkpatrick[9] has given an overview of the different available theories for problems concerning percolation and conductance.

As the material transforms, the martensitic sites will still have a higher electrical resistance, and an increasing number of austenitic sites will have a lower resistance. At some concentration of transformed material a connected path of lower resistance austenitic sites will exist, lowering the overall resistance of the material. Partly due to this process the decrease in resistance will not be linearly dependent on the amount of transformed material.

Because of the large number of degrees of freedom of an electrical resistance problem in a changing medium, COMSOL is used to calculate the resistance at different degrees of transformation. Because COMSOL is a physics based finite element package it shows very good convergence of problems with high accuracy.

A structure with cubic cells was used to represent the material. In the simulation these cells transform in a random order (i.e., a different conductivity is assigned to certain cells). The model had a width and depth of 5 cells and was 100 cells in length in order to represent the slenderness of a thin NiTi wire.

The material properties used in the model were taken from the experiments as explained in section 2.1. The temperature and strain dependence of the martensitic and austenitic phase were combined and a single input was used for the model. Combining these two parameters was done by taking a reference value for both martensite and austenite and computing the temperature and strain difference at every point during the transformation as a function of temperature and strain.

Because of the statistical nature of percolation theory, ten simulation were run with random transformation sequences. Also, two simulations were run with a prescribed transformation sequence. In one case the cells were transformed in layers from the top down, so that the resistance was comparable to resistors in series. In this case percolation would not have any influence.

In the other case the cells transformed in columns so that low resistance material would create a connected path through the medium as fast as possible, comparable to resistors connected parallel to each other. In the latter case percolation would have the largest possible influence. The comparison of these two simulation is done in section 4.

2.3. Experimental Data

The experimental data was obtained by electrically heating a loaded SMA wire. During the experiment the displacement of the mass suspended by the wire was measured. The same wire was used as for determining the material constants (Saes-Getters, SmartFlex, material code 5S0007, 0.4 mm diameter). A mass was suspended from the wire equivalent to 250 MPa (3.203 kg).

Current was supplied to the system by a Delta Elektronika (ES-015) power supply. Over a period of 640 seconds the current was increased from 0 to 1.85 A. The reason for such a slow increase of current is to mitigate time dependent effect as much as possible. The heating cycle was run two times, the first cycle was to remove any load history from the wire, the second cycle is used for the actual correlation. The displacement of the mass suspended by the wire was used to compute the extent of transformation since transformation is the only phenomenon responsible for contraction.

How the resistance changes during the experiment can be seen in Figure 2.

3. Comparison of Model with Experimental Data

In this section the results of the simulation will be discussed first (3.1). The results of the simulation will also be shown together with the measured data for comparison (3.2).

3.1. Results of Simulation

Figure 1 shows the results of the simulation. The behaviour of the resistance is dependent on the order in which the material transforms. Figure 1 shows the average result of 10 simulations with different random transformation sequences for all cells. The maximum difference between these 10 random simulations is 0.02 %.

In Figure 1 it can be seen that the resistance initially increases which is mostly because of the temperature dependence. After roughly 10 % transformation, a steep decrease is initiated because austenite has a lower resistance than martensite. The last part of the graph, after 95 % transformation, shows an increase again, which, as in the first part, is due to the temperature dependence.

Two simulations were done with the most and least influence of percolation. These two results have a maximum difference of only 0.05 %. Therefore, percolation has a very limited influence in this specific case.

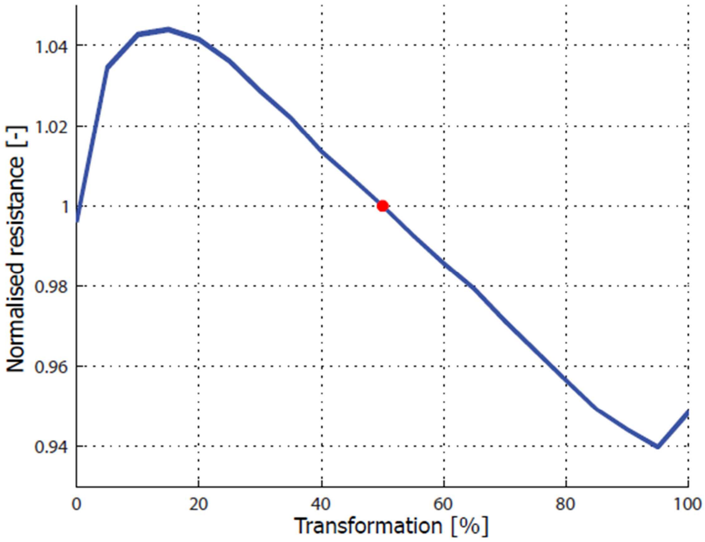

Figure 1: Change in electrical resistance according to the COMSOL simulation. Normalised with respect to 50 % transformation.

3.2. Comparison Between Simulation and Measurement

The comparison between measurement and simulation can be seen in Figure 2. The most apparent difference between the two graphs is the slope with which the resistance decreases during the transformation. However, the trend displayed by the simulation corresponds very well with the measurement. In the next section the differences between the two results is discussed in more detail.

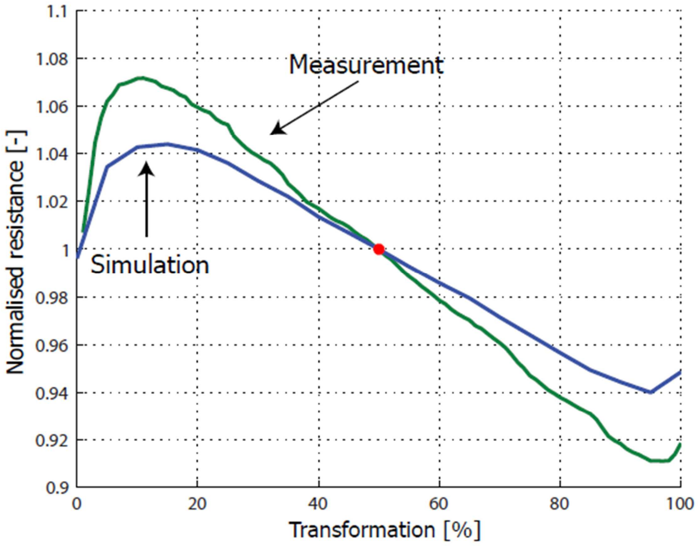

Figure 2: Comparison between the mean of the simulations and experimental data. Results are normalised with respect to 50 % transformation.

4. Discussion

As discussed in section 3.1, the theoretical best and worst case of percolation only differ 0.05 %. That this difference is so small means that the influence of percolation is negligible. Therefore, the change in resistance during the reverse transformation of a NiTi SMA mostly depends on the change in length and temperature. It should be noted that the simulations were done on a cubic structure and that another internal structure might be more influenced by percolation.

If an internal structure more similar to the actual material structure was used for the simulation, the correlation between simulation and measurement will improve. The cubic structure in the simulation has six nearest neighbours, if there are more neighbours for each cell there are more possible routes available for the electricity. In a more interlinked internal structure it is easier to create a path of lower resistance, because regions of austenite can be connected faster. This way percolation will play a more significant role and causes a steeper decrease of resistance explaining the difference in slope between the simulation and experimental data observed in Figure 2.

Another effect that is not taken into account is the linear coefficient of thermal expansion (CTE). While the material is heated it will expand due to the CTE and thereby mask part of the contraction of the material due to the transformation process. Because the temperature does not increase linear during the transformation, as can be seen in Figure 3, the CTE is expected to influence the process mainly in the first and last 10 % of the process. According to the manufacturer of the material[6] the CTE of the martensitic phase is $6.6 \cdot 10^{-6}$ [$°C^{-1}$], for the austenite phase it is $11 \cdot 10^{-6}$[$°C^{-1}$]. This corresponds with an elongation of 0.23 mm during the full transformation (temperature difference of 106 °C), or 3.2 % compared with the contraction due to the full transformation. As a result the actual transformation is 1 % more after the first 10 %, and another 2 % more after the last 10 %. This means that the peaks in the graph should be shifted outward, which will correspond better with the measurement. However, the amplitude of the change in resistance will not change since this is only dependent on the strain and temperature change.

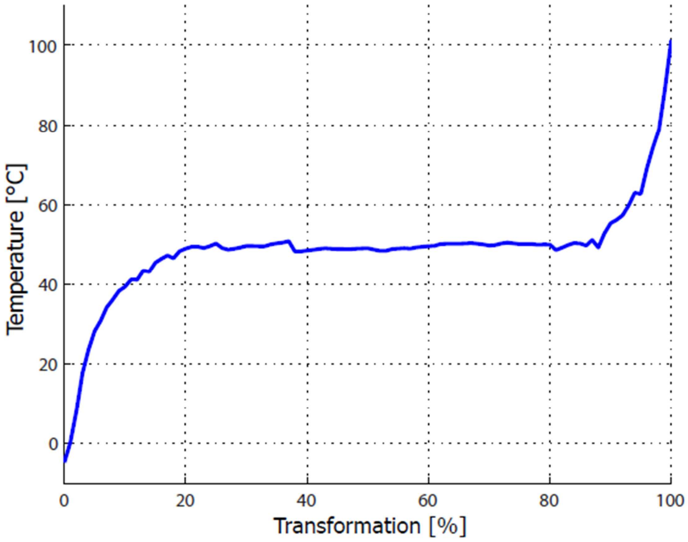

Figure 3: Development of temperature as a function of the transformation.

For the experimental results shown in Figure 2 a fixed mass was used and the heating time was very long (640 s) to mitigate and time variant effects. If, however, the heating time would be dramatically shorter the sudden transformation would cause an uneven internal stress distribution and this will influence the transformation itself and, thereby, the change in resistance. It is important to note that the change in resistance as shown in this paper is at very low transformation speed and is not necessarily applicable to faster heating rates.

Also, this method cannot be used for experiments that use a fixed length of the SMA where the force is increased during the transformation process. Because force and temperature are competing phenomena in terms of transformation the resistance signal displays a lot of noise. This instability can only be reduced if force is implemented in the model as well.

5. Conclusions

It is shown that the non-linear behaviour of the resistance change during the reverse transformation of a shape memory alloy (SMA) wire is understood well. The presented simulation shows good correlation with a measured response. The influence of percolation was calculated to be minimal since the best and worst case showed a difference of only 0.05 %. The simulation was done on a cubic structure, while another structure might show more susceptibility to percolation.

Because a cubic structure was used for the simulation, each cell had six nearest neighbours. If the actual internal structure of the material shows more connectivity between transforming regions, the influence of percolation would be more significant. Increased percolation will result in a steeper decrease of the electrical resistance. This can explain the difference between the gradient of the resistance according to the simulation and the gradient according to the measurement.

Including the coefficient of thermal expansion would also increase the accuracy of the simulation, especially in the first and last 10 % of the transformation range. However, it was shown that the thermal expansion is only a 3 % compared to the contraction due to the transformation. This 3 % difference would not increase the amplitude of the resistance, but the peaks would shift outward and show better correlation to the peaks of the measurement.

The simulation assumes a steady state change in resistance and the results presented in this paper are therefore only applicable to very slow transformation processes. If stress was incorporated in the simulation, and monitored during the test, faster transformation processes could in theory also be simulated.

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