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THE DEVELOPED ALTERNATIVE MODEL TO DESCRIBE THE MICROSTRUCTURAL BEHAVIOUR OF NITI SHAPE MEMORY ALLOY

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ABSTRACT

Shape memory alloy is one of the materials classified as 'smart' materials. Its anomalous behaviour has gained more attention in the field of engineering. There are numerous mathematical models that have been developed to analyze its behaviour. In this paper, a newly developed constitutive model for shape memory alloy is presented. The features of the newly developed model are presented and compared with some of the existing models.

Keywords: Martensite volume fraction, Twinned martensite, Detwinned martensite, Austenite phase.

1. INTRODUCTION

In recent years, convectional structures are being converged to smart structures by introducing smart material. Smart materials are normally composed of group 4-12 elements, also called transition elements. Compounds formed by transition elements use to have unique behaviour. They tends to behave strange way in response to external environmental changes, like pressure, temperature etc. The well known smart materials include vanadium dioxide, shape memory alloy, etc. Vanadium dioxide is a transition metal which exhibit semiconducting properties below 68^{o}C temperature and exhibits metallic properties above 68^{o}C [1]. Shape memory alloy is also a smart material which changes its macrostructure due to temperature change. This paper focuses on the unique behaviour of shape memory alloy (SMA). There are different kinds of SMA which include NiTi, NiTiCu, CuAlNi, and many other metallic systems [2]. SMA macro-structural change is brought by the micro-structural transformation i.e. Martensite transforms to Austenite and visa versa. The phase changes (martensite to austenite and austenite to martensite) occur as a function of both stress and temperature as illustrated in figure 1. SMA has a martensite phase at low temperature where the microstructural atoms are arranged in a zigzag form known as twinned martensite. When the load is applied, the zigzag form will be destroyed such that atoms are arranging themselves, this form is known as detwinned martensite. The two states of martensite will be referred here as martensite variants. SMA was named as memory alloy because it can remember its original shape after being deformed. SMA returns to its original shape when heat is applied unto it. In general when a material is subjected to heat, it becomes soft whereas SMA exhibits the opposite. The recovered shape is accompanied by stress which makes them suitable for actuation applications. SMAs were initially applied in biomedical field and later to engineering field and aerospace industry [3]. In recent years, SMAs are gaining attention in aerospace industry. Numerous models have been reported to describe the macro-structural behavior of SMA [4-11]. In this paper we report the modified model for Liang and Rogers [8]. These models were chosen since they are the basis of the later models developed.

2. PHASE TRANSFORMATION EQUATION FORMULATION

The constitutive law we adopted is the same as the one adopted by Liang and Rogers's model [8]. The difference appears on the phase transformation estimation functions. In this paper we formulated another alternative way to estimate the phase transformation behaviour i.e. tangent functions. The newly formulated phase transformation

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equation (tangent function) can give a final bound of phase transformation of $\xi = 1.0$ whereas Tanaka's model can only give a phase transformation final bound of $\xi = 0.99$. SMA is considered to be transformed fully to martensite phase when this phase transformation final bound is $\xi = 1.0$. The newly formulated model can also give final transformation bound $\xi = 0.0001$ and this bound is associated with a fully austenitic phase of SMA. The transformation of martensite to austenite (heating) is described by the following equation:

$$\xi_{M-A} = \xi_M - \xi_M \tan\left[\iota_A \left(T - A_s\right) + \vartheta_A\right] \quad (1)$$

Equation (1) can be simplified to the following equation by taking out the common factor of ξ_M

$$\xi_{M-A} = \xi_M \left\{1 - \tan\left[\iota_A \left(T - A_s\right) + \vartheta_A\right]\right\} \quad (2)$$

Where ι_A and $\tilde{N}_A$ are the material constants that can be calculated as follows

$$\iota_A = \frac{\pi}{4\left(A_f - A_s\right)} \quad (3)$$

$$\vartheta_A = \frac{b_A \sigma}{5\pi} \quad (4)$$

A_s, A_f, σ are austenitic start and austenitic finish temperatures and applied stress, respectively. The material constant b_A can be calculated as follows

$$b_A = \frac{-\iota}{C_A} \quad (5)$$

Where C_A is the representative of the change in transformation temperatures, A_s and A_f, with the applied stress [8]. The transformation of austenite to martensite is described by the following equation

$$\xi_{A-M} = \beta - B \tan\left[\iota_M \left(T - A_s\right) + \vartheta_M\right] \quad (6)$$

Where the material constants, $\beta, B, \iota_M, \vartheta_M$ can be calculated as follows

$$\beta = 2\left(\frac{1+\xi_A}{2}\right) \quad (7)$$

$$B = 1 - \xi_A \quad (8)$$

$$\iota_M = \frac{\pi}{4\left(M_s - M_f\right)} \quad (9)$$

$$\vartheta_M = \frac{b_M \sigma}{5\pi} \quad (10)$$

M_s, M_f are martensitic start and martensitic finish temperatures, respectively. The material constant b_M can be calculated as follows

$$b_M = \frac{-\iota_M}{C_M} \quad (11)$$

, where C_M is the representative of the change in transformation temperatures, M_s and M_f, with the applied stress. The transformation strain during heating and cooling can be easily by multiplying equation (2) and (6) with the maximum recovery strain, ε_L. The value of ε_L is measured experimentally. However, the transformation strain associated with heating is given by

$$\varepsilon_{M-A} = \varepsilon_L \xi_{M-A} \quad (12)$$

The transformation strain associated with cooling is given by

$$\varepsilon_{A-M} = \varepsilon_L \xi_{A-M} \quad (13)$$

The numerical simulation results are discussed in the following section.

3. NUMERICAL SIMULATION RESULTS AND DISCUSSION

The newly developed phase transformation model has been utilized to predict the phase transformation and mechanical behaviour of SMA. The results are compared with those predicted using Liang and Rogers's model. The numerical simulation results were conducted using FORTRAN programming language. The constants used for simulation are tabulated in table 1. Figure 2 shows a stress free state phase transformation during heating and cooling described by new model. SMA is assumed to be at detwinned martensitic phase when undergoing to the process of heating. During heating, SMA starts to transform from detwinned martensite to austenite phase at austenitic start temperature (68.22 °C) and become full austenite at austenitic finish temperature (78.01 °C) hence martensite volume fraction decreases from 1.0 to 0. During cooling, austenite starts to transform to twinned martensite phase at martensitic start temperature (52.11 °C) and become full martensite phase at martensitic finish temperature hence martensite volume fraction increases from 0 to 1.0.

Figure 3 and figure 4 show a phase transformation during at different stresses predicted by Liang and Rogers's model and current model, respectively. According to Liang and Rogers's model, the phase transformation curves follow almost the same path even though the SMA is under constant stress whereas the current model shows a variation with the applied stress. The current model can estimate clearly the effect of the applied stress on transformation curves of SMA. The temperature-strain curves are shown in figure 5. The maximum recoverable strain during the phase transformation is approximately 8%. It is clearly seen from the graph that there is no transformation strain observed after austenitic finish temperature (78.01 °C). The graph becomes flat after the austenitic finish temperature. The transformation stress was also predicted using the current model shown in figure 6. It is clearly observed from the graph that the maximum stress is attained during heating and low stress is attained during cooling. The graph also shows that no stress observed after the austenitic finish temperature hence full austenite phase.

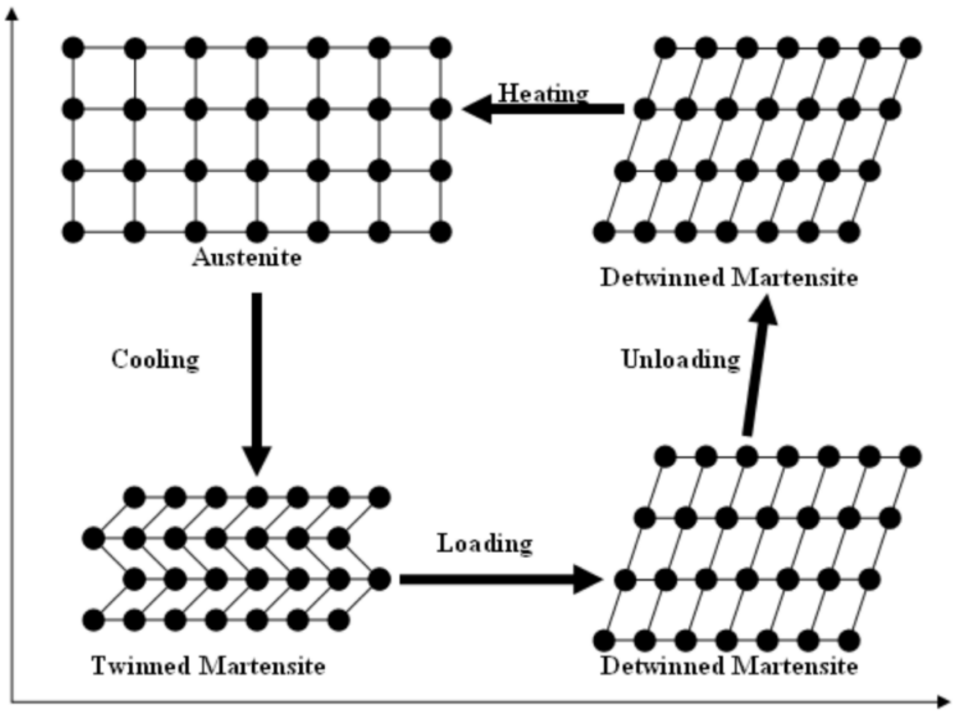

Figure 1: SMA microstructural Behaviour

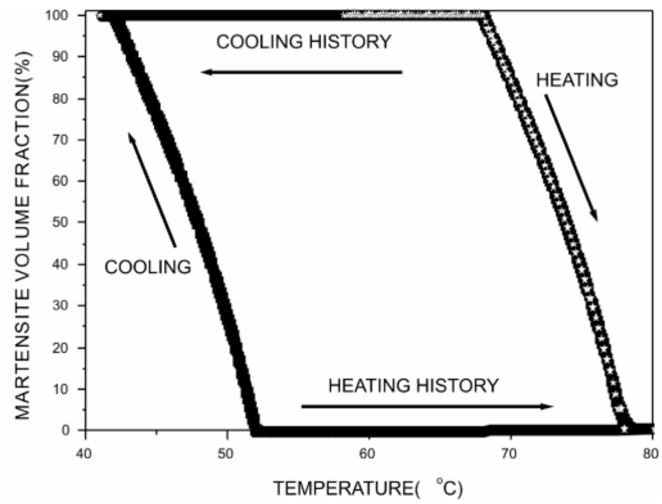

Figure 2: Temperature-phase Transformation Diagram

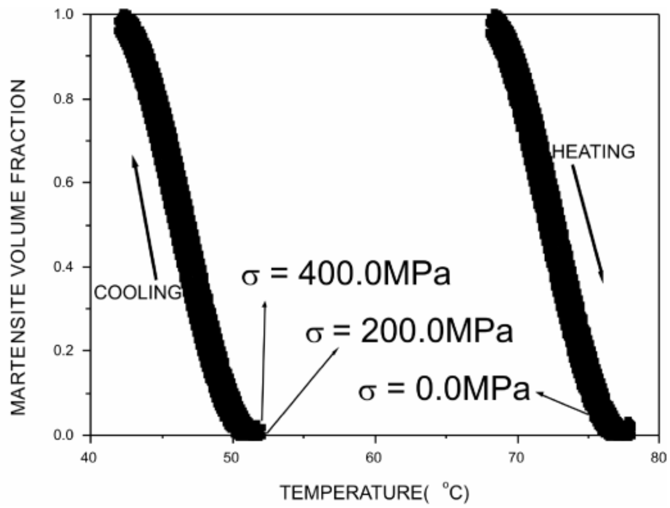

Figure 3: Temperature-martensite Volume Fraction Diagram at Different Stresses by Liang and Rogers's Model

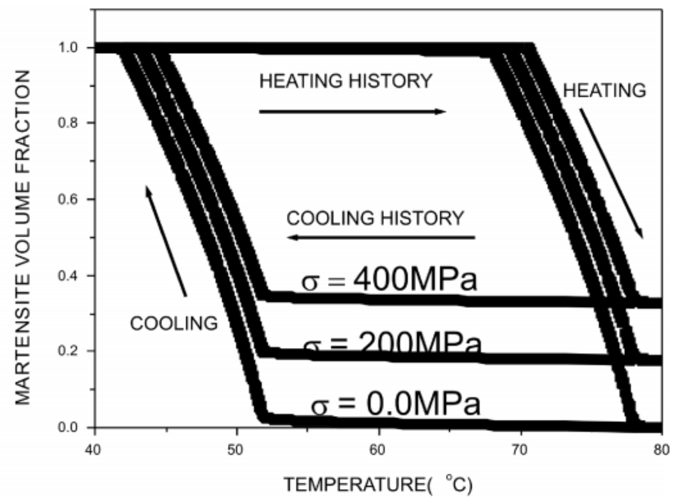

Figure 4: Temperature-martensite Volume Fraction Diagram at Different Stresses by Current Model

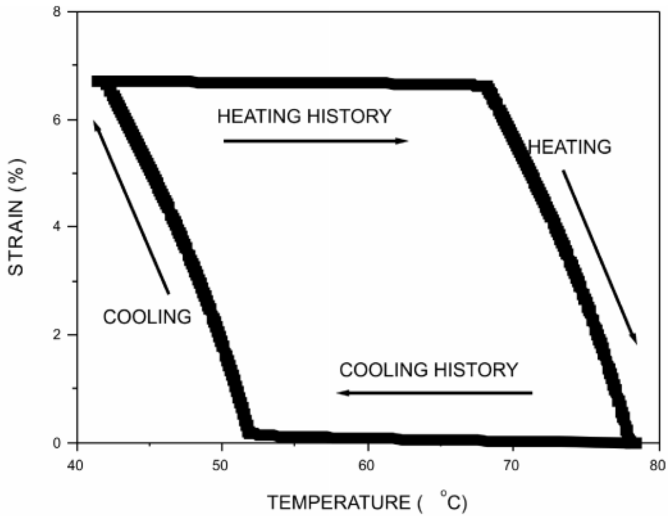

Figure 5: Temperature-strain Diagram

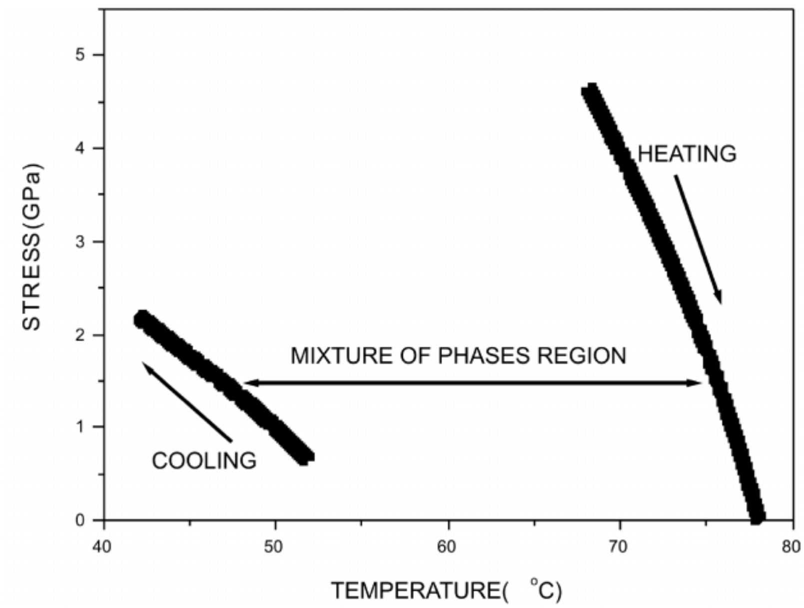

Figure 6: Temperature-stress Diagram

4. CONCLUSION

The new phase transformation model describing the behaviour of SMA has been developed. The developed model proves to be one of an alternative option to describe the SMA behaviour. The simulation results attained from the current model correlates with the macroscopic behaviour of SMA observed in the literature [10]. The effect of variation of simulation parameters can be clearly observed. Different aspects of SMA have been simulated using the current model. The current model seems to clearly show some features that are not clearly observed from the existing models. This has been observed in figure 4 when the transformation occurs under different applied stress.

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