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Generation and stability of reversible shape change in NiTi memory alloys

A.C. Kneissl & H. Scherngell
Institute of Physical Metallurgy and Materials Testing, University of Leoben, A-8700 Leoben, Austria
EMail: kneissl@unileoben.ac.at

Abstract

Shape Memory Alloys (SMA) are promising materials for actuator components. This work focuses on the principal aspects underlying the deformation phenomenon known as Two-Way Shape Memory Effect (TWSME). On wire specimens of a near equiatomic NiTi alloy such an effect is achieved by a thermomechanical treatment. Depending on the training parameters and heat treatment conditions, different magnitudes of reversible shape change are obtained. Further experimental work concentrates on the stability of this special effect throughout cyclic application. Again a strong influence of the initial microstructure on the degradation characteristic is observed.

1 Introduction

The term shape memory refers to the ability of certain alloys to restore their original shape after having experienced a considerable deformation. This phenomenon originates primarily from a thermoelastic martensitic phase transformation, which is characterised as being crystallographically reversible. Meanwhile, this special behaviour has been proved on several alloys, but only a few have gained commercial significance. Due to superior functional and mechanical properties, the intermetallic compound NiTi is the most frequently used shape memory alloy up to now and has been successfully introduced in a variety of technical and medical applications. The region of homogeneity of the intermetallic compound NiTi is quite small (Figure 1). By changing the composition within this region, the transformation temperature can be changed from –100°C to +100°C [1]. The functional as well as the mechanical properties can be further adjusted by adding appropriate ternary elements [2]. Excellent properties concerning corrosion resistance, work output, fatigue lifetime and electrical resistivity make this group of alloys to the most favourable for shape memory actuators.

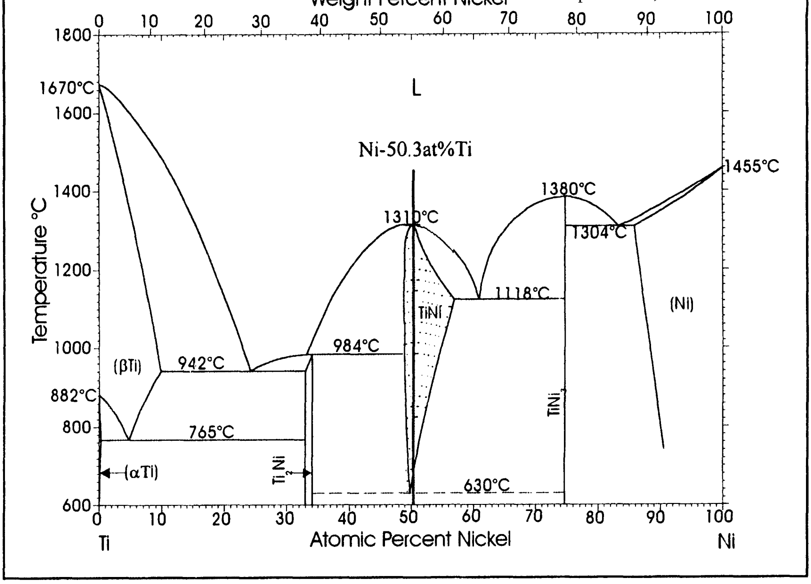

Figure 1: NiTi Phase Diagram, after [3]

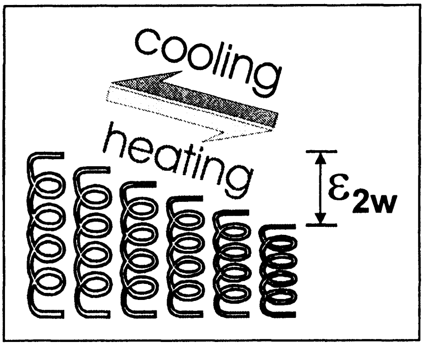

Figure 2 : Shape change of a trained element, schematically

Nowadays, the function of most shape memory elements integrated in smart structures is based on the so-called one-way shape memory effect. This specific behaviour of a prestrained SMA specimen which is characterised by recovering the strain during heating, is used to generate either large motions or high forces in response to temperature changes. If this effect is to be used repeatedly – e.g. in the case of a thermosensitive

…uating element – an external force has to be applied, usually a bias spring, to reset the element to its strained condition after each action. Compared to other actuation methods, shape memory alloys are simpler in design, more silent and more compact. But especially in the case of micro-scale actuators, the required consideration of the resetting force may cause constructive, dimensional or functional restrictions. However, it is possible to train a shape memory element to change its shape during heating and cooling as well, both without the assistance of an external force. As this is not an inherent characteristic of this material, it is necessary to subject the material to a preliminary training procedure in order to obtain this behaviour [4].

A trained element changes between two preset shapes whenever the temperature is changed within a particular range (Figure 2). Such an element can either be applied as a thermal sensor or as an electrical actuator, if the heating is done by the Joule´s effect. It is essential for such elements that the functional parameters stay stable throughout the cyclic application. Special consideration will be paid in this work to this important criterion for the actual use of shape memory elements.

2. Experimental

The investigations have been carried out on wire specimens of a binary NiTi alloy with a nominal composition of Ni-50.3at%Ti. Two heat treatment conditions were investigated since previous studies [5] have shown a strong influence of the microstructure on the shape memory behaviour. W1 represents the cold worked condition (after wire drawing) while W2 refers to the samples annealed at 550°C/20min/WQ after cold working.

First of all, a characterisation of the samples' functional properties was carried out. This refers to the determination of the phase transformation temperatures (switching temperatures of the actuator) and the recoverable strain (available shape memory motion). The martensitic transformation, and consequently also the shape change, does not occur at a single temperature but throughout a temperature range. Moreover, the forward transformation, indicated by M_s, M_f, takes place at a different temperature compared to the reverse transformation (A_s, A_f). Figure 3 illustrates schematically the progress of the phase transformation on cooling and heating. The hysteresis is about 20°C and can be modified by ternary alloying elements or microstructural modifications.

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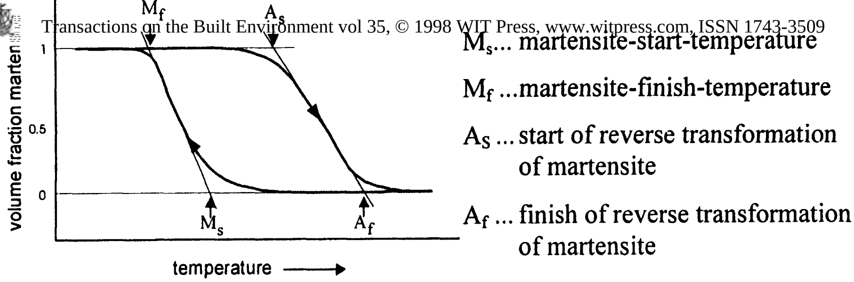

Figure 3: Martensitic transformation on cooling and heating

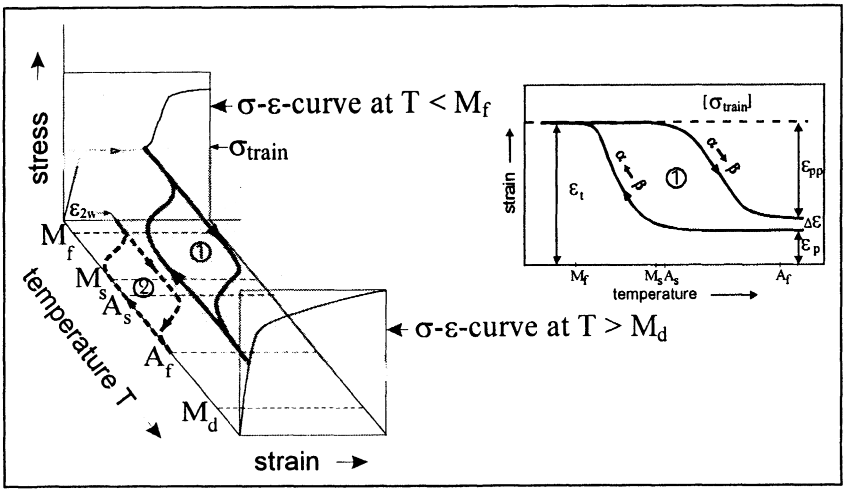

Figure 4: Illustration of the applied thermomechanical training procedure
1: Training cycle; 2: free thermal cycle after training
1 enlarged: schematic illustration of a training cycle indicating the labelling of the different strains: ε_t: total strain; ε_{pp}: pseudoplastic strain; ε_p: cumulative irreversible strain; $\Delta\varepsilon$: irreversible strain per training cycle

The transformation temperatures have been deduced from electrical resistance versus temperature curves. The changes in the electrical restistivity of the samples were measured by a four point direct current method. Changes of electrical resistance versus temperature have proven to be a quite reliable tool for monitoring the phase transformation.
The thermomechanical training to create a uniaxial TWSME consisted in thermally cycling the wire specimen through the entire transformation range under constant stress for several times. Figure 4 illustrates sche-

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...tically the applied procedure. Heating of the wire specimens was done by direct passage of current, cooling by pressurised air. Most actuators are also heated by Joule's effect making fast actions possible. The limiting operation is cooling as natural convection is quite slow.
Subsequently to the training, the stability of the obtained effect was studied by repeated thermal cycling the trained specimen without any external force, while measuring the shape change.

3. Results and Discussion

Figure 5 illustrates the course of the electrical resistance throughout a thermal cycle from below M_f to above A_f. The first deflection of the curve on cooling from the high-temperature modification corresponds to the beginning of the forward transformation M_s. The transformation sequence leads via distorted intermediate phases to the crystal structure of the martensite. The corresponding strains cause an increase of resistivity during transformation. The finish of the forward transformation M_f is related to the point, where the resistivity runs again parallel to the ascending branch of the curve. The start of the reverse transformation A_s is again indicated by the deviation from the linear course, while A_f is represented by the merging point of the ascending and descending branches. The electrical resistance is a suitable parameter to control the shape change of an actuator. Though, as the resistivity depends strongly on the microstructure, the actual appearance of the curve will vary according to heat treatment condition and composition [6].
The stress-strain diagram in Figure 6 shows the deformation behaviour of the specimens in the martensitic modification. After reaching a critical stress level, deformation by processes like moving of twin boundaries and reorientation of different martensite variants takes place. This pseudoplastic deformation is characterised by a near-horizontal yield plateau, the so called martensite plateau. Within this plateau the deformation is based on reversible processes only. Its extension represents the maximal recoverable strain. The cold worked specimen W0 exhibits a shorter and more inclined plateau because a lot of microstructural defects have been introduced during cold working, which inhibit the reorientation of martensite variants during tensile test [7]. Annealing at 550°C causes partial recovery, resulting in a broader plateau at a lower stress level.
The shape memory behaviour is illustrated best by the strain-temperature relationship. Figure 7 shows the strain-temperature curves as they have been recorded by microstrain measurement during the training cycles.

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During cooling of the loaded SMA specimen, stress induced martensite will be formed. Normally, the NiTi martensite consists of 24 variants, that are crystallographically equivalent [8]. But the applied stress causes preferred nucleation and growth of those variants, that have the highest compatibility with the present strain-field. This orientation of the martensite results in a macroscopic strain in direction of the applied stress, as can be observed in Figure 7. On heating, the alloy transforms back and therefore is forced to restore the associated original shape.

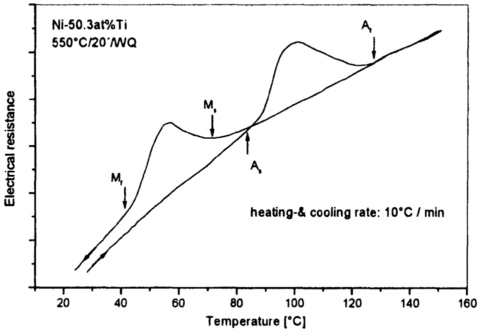

Figure 5: Electrical resistance versus temperature curve indicating the phase transformation temperatures for the sample W1

Table 1: Transformation Temperatures of the investigated alloy in different heat treatment conditions

	W0	W1
M_f [°C]	38	42
M_s [°C]	65	69
A_s [°C]	82	84
A_f [°C]	141	127

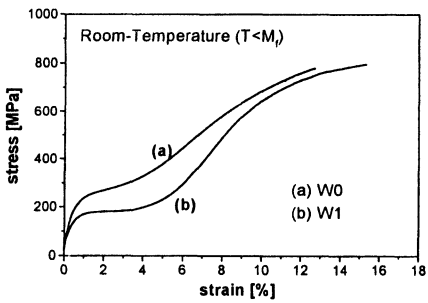

Figure 6: Stress-strain curves of the martensitic modification

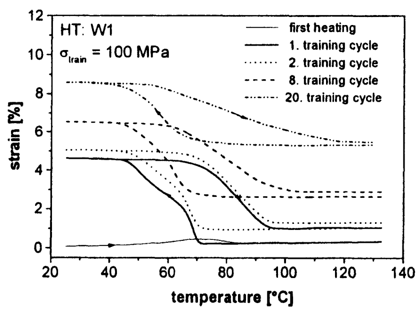

Figure 7: Illustration of some training cycles

Figure 8 and Figure 9 show the course of the different strains during thermomechanical two-way training for different heat treatment conditions. The increase of the pseudoplastic strain ε_{pp} during training is a direct consequence of the continual development of the TWSME. The trained shape is memorised by leaving behind some information in the high temperature modification. In the first place such features are stabilised martensite and dislocations [9]. The dislocation structure responsible for the growth of ε_{pp} is also responsible for the development of the TWSME. It is interesting to note from Figure 8 that ε_{pp} of the annealed specimen shows a maximum value and decreases with further training cycles. Apparently, the irreversible strain rises too fast. This is quite important as it has been concluded elsewhere [10], that there exists a near proportionality between the pseudoplastic strain and the obtained two-way strain. This suggests that in order to maximise ε_{2w}, fewer than 20 training cycles should be applied. This is confirmed by the values listed in Table 2. The two-way strain obtained after 10 training cycles is larger than after 20 cycles.

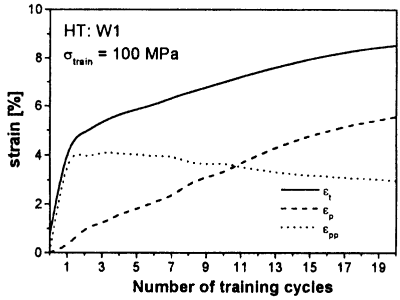

Figure 8: Development of different strains during training, annealed, 100 MPa

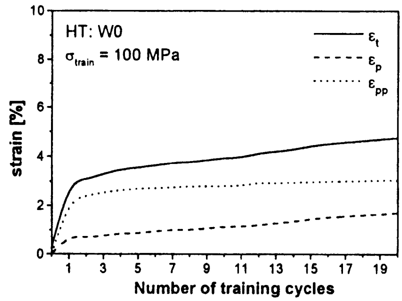

Figure 9: Development of different strains during training, cold worked, 100 MPa

As mentioned earlier, it is very important to determine the stability of the TWSME during thermal cycling. It is evident from Figure 10 to Figure 12 that the degradation of the TWSME due to stress-free thermal cycling shows for the different conditions similar characteristic features. There is a rather strong decay during the first 50 to 100 thermal cycles which gradually decreases by further cycling. After about 500 cycles, the degradation becomes fairly small and for the cold worked condition, the TWSME is practically stable.

Considering the importance of the microstructure for the appearance of the TWSME, it appears very likely, that the decrease of ε_{2w} is the consequence of changes in the substructure. Investigations by Miyazaki et al. [11] showed, that thermal cycling causes a rearrangement and annihilation of existing dislocations as well as the introduction of additional ones. Both processes change considerably the dislocation pattern that has

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een created during the training cycles and will therefore lead to an increasing amount of unfavourably oriented martensite. Some hints about the actually controlling mechanism may be obtained by comparing the degradation of the cold worked specimen in Figure 10 to a annealed one in Figure 11. While the initial decay cannot be avoided, the decrease in the latter stage shows a sensitivity from the initial dislocation density. In the annealed specimen, the two-way strain keeps degrading throughout the investigated range of 1500 thermal cycles, whereas in the cold worked sample it becomes stable. It may be suggested from this observation, that the degradation in this stage is primarily due to the introduction of dislocations. In the cold worked sample it is more difficult to generate additional dislocations as the dislocation density is already very high. This results in a more stable TWSME in the latter stage.

Table 2: ε_{2W} obtained with different training parameters

HT	W0	W1	W1
σ_{train} [MPa]	100	100	100
N_{train}	20	20	10
ε_{2W} [%]	**1,18**	**1,80**	**2,15**

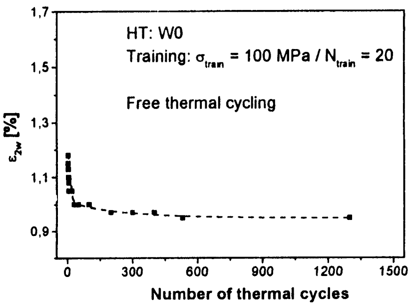

Figure 10: Degradation of the TWSME due to thermal cycling, W0

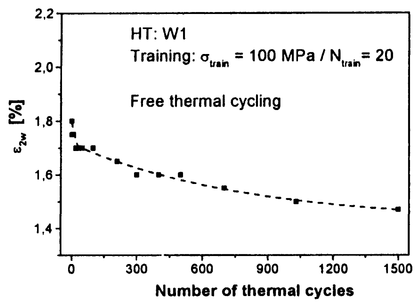

Figure 11: Degradation of the TWSME due to thermal cycling

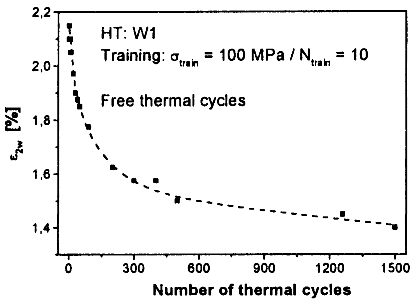

Figure 12: Degradation of the TWSME due to thermal cycling

On the other hand, the sharp decay at the beginning of thermal cycling appears to be not affected by a higher dislocation density. Moreover, it seems to be a transient phenomenon which is limited to the first 50 to 100 cycles, reaching a saturation at the end of the initial period. It appears very likely that the decrease in this range corresponds to a continual change in the dislocation substructure - by rearrangement and annihilation - until a stable configuration, representative of the saturated state, is reached.

It should be further noted, that even on variation of the training parameters, the characteristic features of the degradation curve remain more or less the same. It becomes evident, that for the applied training procedure, the initial microstructure of the alloy influences the stability of the intrinsic TWSME far more than the training parameters.

4. Conclusions

With the chosen training procedure a maximum two-way strain of 2,1% could be achieved. Considering the fact that the motion of shape memory actuators is not limited to such a simple mode as linear shape change, a two-way strain of this magnitude is quite attractive.

The induced intrinsic TWSME shows a sharp decay in the early stage of cyclic application. This is ascribed to the rearrangement and annihilation of dislocations during the first few thermal cycles until a new saturated state is reached. In the latter stage, the degradation rate is smaller and it shows a dependence from the preliminary heat-treatment. It is suggested that in this stage the degradation is controlled by the introduction of additional dislocations. The preliminary heat-treatment appears to be the crucial parameter to optimise the TWSME regarding magnitude and stability.

Acknowledgement

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