Transformation Cyclic Damage of Near-equatomic Ni-Ti

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Abstract. Near-equatomic Ni-Ti alloys are known to exhibit shape memory effect associated with a B2 ↔ B19’ martensitic transformation. These alloys are often used in various cyclic modes in application, typically as actuators and sensors. The B2 ↔ B19’ martensitic transformation in Ni-Ti is accompanied with a large lattice distortion. Cycling through this transformation, induced thermally, mechanically or by the combination of the two, is found to cause structural damage to the alloys, hence changes their functional properties. This study investigates the effect of transformation cycling and heat treatment on the property stability of near-equatomic Ti-Ni. It was found that in the case of thermally induced transformation cycling, incomplete transformation cycles caused less structural damage to the matrix than full transformation cycles whereas in the case of mechanically induced transformation cycling via pseudoelasticity in tension, partial or full transformation cycling caused similar property changes. The indifference of the case of pseudoelastic cycling is attributed to the localisation of the deformation, commonly known as the Lüders-type deformation.

Introduction

Near-equatomic Ni-Ti alloys exhibit shape memory effect and pseudoelasticity. The shape memory effect refers to the behaviour of the material to restore its original shape when heated after deformation [1]. The pseudoelastic property refers to the material’s behaviour of spontaneous deformation recovery of excessively large strains upon unloading in an inelastic manner [2]. The shape memory effect and pseudoelasticity in these alloys are associated with a B2 ↔ B19’ thermoelastic martensitic transformation. The ability of the alloys to exhibit large recoverable shape changes, typically >6% strains in tension, stems from the fact that the B2 ↔ B19’ martensitic transformation is associated with large lattice distortions. In this regard, the transformation process is also a mechanical process at the microscopic scale. Such large microscopic lattice distortions cause inevitable internal plastic damages to the matrix.

In exhibiting these shape changes, or deformation recoveries, the alloys perform a mechanical work. Owing to this novel property the alloys have been used in a wide range of applications, often as actuators and sensors. In these applications the Ni-Ti components often experience repeated transformation cycles, either under external load or free of constraint. One critical concern in the development of applicable shape memory devices is the property stability of the alloys. It is known that the critical temperatures and the critical stresses for the B2 ↔ B19’ martensitic transformation in Ni-Ti are sensitively affected by transformation cycling, in both thermal and mechanical cycles [3-6]. Both these two parameters are critical design and performance parameters. Therefore, understanding of the effects of transformation cycling on the transformation behaviour and improvement of the property stability during transformation cycling have been critical concerns for the application of these alloys.
It has been well documented in the literature that thermal cycling causes continuous decrease of the transformation temperatures and enlarges the temperature hysteresis [3,4]. Mechanical pseudoelastic cycling, on the other hand, causes continuous decrease of the critical stress for inducing the transformation and reduces the stress hysteresis [5,6]. These changes in property parameters are indicative to internal damages, i.e. internal plastic deformation, of the matrix. To overcome this problem, there have been suggestions and various efforts to enhance the property stability of Ni-Ti, such as by precipitation strengthening for Ni-rich Ni-Ti alloys, partial anneal after cold working, or pre-cycling for stabilisation. Retrospectively, there have also been suggestions to make partial uses of the full transformation shape memory effect in applications to minimize the shift of property parameters and to extend the service life of the components. Despite all these empirical solutions to the problem, there has not been a clear understanding of the occurrence of internal plastic deformation during the cycling beyond the knowledge that dislocations are generated during thermal cycling [7], nor practical data on the effect of various partial cycles on the transformation behaviour. This study investigated the effects of partial thermal and mechanical cycling on the internal damages of near-equiatomic Ni-Ti alloys.

**Experimental Methods**

Commercial polycrystalline Ni-Ti alloys were used in this study. The alloy used for thermal cycling had a nominal composition of Ti-50.2at%Ni and was in annealed state. The alloy used for tensile pseudoelastic cycling had a nominal composition of Ti-50.8at%Ni and was in wire form of 0.25 mm in diameter. The alloy used for ferroelastic cycling in shear had a nominal composition of 50.2at%. The thermal cycling was conducted and measured using a Perkin-Elmer DSC-4 differential scanning calorimeter (DSC) at heating/cooling rate of 10 K/min. Mechanical cycling was conducted using an Instron 8501 machine equipped with a thermal bath for temperature control.

**Results**

Fig. 1 shows the DSC measurement of the full and partial thermal transformation cycles. Two samples were used, one for each mode of cycling. The partial cycle was conducted between the full austenite state and the half-martensite state. The peak temperatures, $M^*$ for the forward transformations and $A^*$ for the reverse transformation, were determined from the measurements. Fig. 2 shows the effect of thermal transformation cycling on the two characteristic temperatures. It is seen that the two cycling showed no difference in their effects on the reverse transformation temperature ($A^*$), whereas the critical temperature for the forward transformation ($M^*$) decreased more rapidly during full transformation cycling than during the partial cycling. This implies that the full transformation cycling is more damaging to the internal structure of the matrix.

Fig. 3 shows selected stress-strain curves of two samples subjected to pseudoelastic cycling. Sample (a) was cycled to 2.5% of total strain, corresponding to an early stage of the stress plateau associated with the stress-induced martensitic transformation. Sample (b) was cycled to the end of the stress plateau to achieve a complete transformation. The stress plateau is indicative of localized deformation, i.e. Lüders-type deformation. The insets above the stress-strain curves indicate schematically the deformation localization situation at the maximum strains of the two samples. The section of the larger diameter indicates the original, undeformed austenite. The section of the smaller diameter indicates the stress-induced martensite. The critical stresses for the stress induced transformation, $\sigma_f$ for the forward transformation and $\sigma_r$ for the reverse transformation, of the two samples are shown in Figure 4 for comparison. It is evident that the partial pseudoelastic cycle and the full pseudoelastic showed practically identical effect on the transformation stresses.

Fig. 5 shows stress-strain curves of ferroelastic cycling in shear of three samples. Ferroelastic deformation occurs by the reorientation of martensite variants. The deformation was uniform, as
evidenced by the absence of Lüders-type stress plateau. During cycling the hysteresis loop evolved gradually, with the characteristic stresses at the extremes of the hysteresis loop, $\sigma_c$, increasing progressively with increasing the number of cycles. Figure 6 shows the evolution of the characteristic stress during the cycling, expressed as the increment of the stress from that in the first cycle ($\Delta\sigma_c$) to eliminate the difference in the stress levels of the three samples for direct comparison. It is evident that cycling to larger strains caused greater increases of $\Delta\sigma_c$.

![Schematic DSC curves of the partial forward and full thermal transformation cycles.](image1)

Fig. 1. Schematic DSC curves of the partial forward and full thermal transformation cycles.

![Effect of thermal transformation cycling on transformation temperatures.](image2)

Fig. 2. Effect of thermal transformation cycling on transformation temperatures.

![Tensile stress-strain curves of pseudoelastic cycling of Ti-50.8at%Ni.](image3)

Fig. 3. Tensile stress-strain curves of pseudoelastic cycling of Ti-50.8at%Ni. Sample (a) was cycled to 2.5% strain and sample (b) was cycled to the completion of the stress plateau. The inset above the two sets of curves schematically illustrated the localization situation of the deformations.

![Effect of pseudoelastic cycling on the critical stresses for the stress-induced martensitic transformation.](image4)

Fig. 4. Effect of pseudoelastic cycling on the critical stresses for the stress-induced martensitic transformation.

**Discussions and Conclusions**

The experimental evidences shown above indicate that partial thermal cycling causes less damage to the matrix than the full thermal cycling. In the case of mechanical pseudoelastic cycling, the degree of damage was the same for the partial and the full cycles. For ferroelastic deformation, cycling over larger strain spans was more damaging compared to cycling over smaller strain spans. These observations indicate that partial cycling in the form of thermal transformation and of deformation in
shear via martensite reorientation are effective in extending the service life of Ni-Ti shape memory components; whereas in the case of pseudoelastic deformation in tension of thin wire samples, partial cycling is ineffective for extending the service life.

![Graph showing shear stress-strain curves of ferroelastic cycling via martensite reorientation of Ti-50.2at%Ni. Three samples were cycled to different levels of shear strains.]

![Graph showing effect of ferroelastic cycling on characteristic stress at the extreme of the ferroelastic cycles, exhibited as the increments from that in the first cycle.]

The difference between the pseudoelastic cycling and the ferroelastic cycling, both mechanical deformation cycling, is caused by the localization of deformation. The pseudoelastic cycling proceeded via a typical Lüders-type deformation. In this case the gauge length of the sample contained two discrete deformation conditions. The sections of stress-induced martensitic transformation had experienced a tensile strain corresponding to the end of the stress plateau and the sections of the original austenite maintained only the initial strain corresponding to the onset of the stress plateau. Continuation of deformation over the stress plateau merely extends the length fraction of stress-induced martensite, without affecting the degree of damage inside the section. Therefore, partial deformation only reduces the length of the material that is damaged, but not the extent of the internal damage the deformed parts have endured. In the case of the ferroelastic cycling in shear, the deformation is uniform. Continuation of deformation into high strain levels simply increases the internal stress levels and the level of internal damages. Thermally induced transformation is also a macroscopically uniform process. The internal stresses created by the formation of martensite increases with increasing the extent of the transformation, thus the increased damage for the fuller transformation cycles.

References