Oral Reference: ICF100814OR

Deformation Behavior of [001] NiTi Single Crystals

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Abstract

We report on the unusual deformation behavior of [001] single crystals of NiTi alloys in compression. Two compositions of NiTi with Ni contents (50.8 and 51.5% at. Ni) were examined. Pseudoelastic deformation occured at both 25°C and 167°C in compression loading. The reason for the higher pseudoelastic behavior temperature range is attributed to the suppression of slip due to the lack of favorable slip systems in the [001] orientation. The results point that with suitable orientation control the pseudoelastic behavior can be extended to high temperatures. The transformation strains for the 50.8% at. and 51.5% at. Ni alloys were established via temperature cycling under compressive stress as 4.0% and 2.5% respectively. The 50.8%Ni results compared favorably with the theoretical prediction of 4.38%.

Keywords

Shape memory, phase transformation, pseudoelasticity, austenite,martensite, slip, temperature cycling

Introduction

The NiTi alloys are a special class of materials which exhibit reversible transformations from austenite(B2) to martensite (B19') and then martensite (B19') to austenite (B2). The transformation can be induced via a change in temperature or the application of stress at temperatures exceeding the martensite start temperature, M_s. In both cases the transformation depends on the crystal orientation, and the loading direction because the habit planes associated with the transformation are of low symmetry and the transformation is directional. Most experimental work confirm that Type II <011> twins have been established in the B19' martensite [1]. Theoretical calculations have been carried out to predict the twin types and the associated habit planes[2]. It has been shown [2] that if slip deformation occurs during transformation, this reduces the transformation strains. The slip deformation occurs readily with loading along certain crystal orientations but is difficult in specific orientations. The [001] orientation can not slip due to the lack of available slip systems. Experimental studies [3] have shown that <001>{100} and <001>{110} are the dominant slip systems in the B2 phase of NiTi alloys. Also, the B2 phase has been shown to undergo twinning at high temperatures [3]. Therefore, the [001] orientation is particularly attractive to achieve transformation at elevated temperatures where slip restricts the transformation.

Another factor that plays a significant role in the transformation process is the presence of precipitates in the material. These precipitates lower the transformation stress (in the peak aged condition) due to the coherency stress fields. In the overaged case, they provide barriers to dislocation motion and also reduce the Ni content in the matrix domains increasing the martensite start and austenite finish temperatures. For example, for the 51.5%Ni alloys the martensite start temperature increases from <-200°C (77K) in the solutionized case to –37°C (236K) for the overaged case. The increase in martensite start temperature with aging for the 50.8% is less dramatic and this increase is from -98°C (175K) in the solutionized case to -55°C(218K) for the overaged case.

The purpose of the present work is to demonstrate the stress-strain response of binary NiTi single crystals with two different compositions under compressive loads. By choosing the orientation ([001]) that minimizes slip deformation, both compositions exhibited pseudoleastic deformation behavior over a temperature range near 200°C which is a factor of two higher than the early works in NiTi alloys [4]. The paper also establishes the transformation strains upon temperature cycling under stress for the 50.8% at. Ni and 51.5% at. Ni compositions as 4.0% and 2.5% respectively. These experiments also provide insight into the martensite and austenite start and finish temperatures for the two compositions under thermomechanical loads.

Experimental Results

Single crystal Ti-50.8 and 51.5% at. Ni samples were prepared from ingots cast by Special Metals Co. The single crystal samples were grown by the Bridgman technique in an inert gas atmosphere. The orientation of single crystal specimens was determined by using electron back-scattered diffraction patterns. Solutionizing of the specimens was conducted at 1000°C(1273K) for 2 hours in an inert gas atmosphere. Then, the specimens were aged at 550°C(823K) for 1.5 hours and this treatment is designated as 'overaged'. The precipitate size is in the range 300-400nm for the 50.8%Ni case while it is about 750nm in the 51.5%Ni case. The introduction of Ni near 51.5% increases the volume fraction of the precipitates considerably with concomitant increases in overall strength of the austenite and martensite phases. Figure 1(a) is transmission electron microscopy (TEM) bright field image that illustrates the precipitates. There are four variants of precipitates but only two are visible under the imaging conditions employed to record this picture. In Figure 1(b) the precipitates after the same aging treatment are shown for the 50.8%Ni composition.

There are two ways to evaluate the behavior of transforming alloys. The first method is to investigate the stress-strain response under loading and unloading at a constant temperature. The second method is to cycle the temperature under constant stress and monitor the strains. In Figure 2, the stress-strain response at 25°C(298K) and 167°(440K) is shown for the 51.5% at.Ni and 50.8% at. Ni cases. The loading and unloading paths are illustrated with the arrows. Three observations are noteworthy.

Firstly, the strength levels where pseudoelasticity is observed extends to stresses as high as 1500MPa at 440K which is unusually high for NiTi alloys. Secondly, pseudoelasticity is observed at room temperature 25°C as well as at 167°C for both compositions with pseudoelasticity of 100% for the 51.5%Ni composition. Thirdly, the transformation region in 50.8%Ni material extends to higher strains compared to the 51.5%Ni case as seen in the 25°C data. This point is further elaborated in Figure 3.

In Figure 3, the strain-temperature behavior is presented under temperature cycling conditions. The strain temperature path is illustrated with the arrows upon cooling and heating. The transformation strains for 50.8% and 51.%Ni compositions were determined as 4% and 2.5% respectively. The stress level was maintained constant during the experiments. This stress level was chosen high enough to produce the growth of the most favorably oriented variant with respect to others and low enough to minimize inelastic deformation and ratchetting of the strains during thermal cycling. Some ratchetting in the compressive strain direction has occurred in the 50.8% Ni case (Figure 3) and this is subtracted from the overall strain range to determine the transformation strain. The stress levels applied for the two compositions differ considerably, and the level of stress is primarily dictated by the flow properties near the martensite start temperature. Since the resistance to transformation is lowest near the M_s temperature, the application of high stress levels near M_s could produce inelastic flow altering the transformation strain trends. The transformation strains from these experiments are summarized in Table 1 where the theoretical value for transformation in compression for the [001] orientation is also listed as 4.38%.

We note that the martensite start temperatures can be determined accurately from Figure 3 by observing the rapid change in strain with spontaneous transformation. The levels are near -28°C for the 51.5%Ni and –47°C for the 50.8%Ni case. These results are consistent with the slightly lower transformation stress observed for the 51.5% at. Ni case in Figure 2 compared to the 50.8%at. Ni case. Some degree of difference between DSC and the transformation temperatures under stress is expected based on the thermodynamics considerations as well as the preferred variant formation corresponding to the stress-induced transformation. A comparison of the transformation temperatures based on the DSC measurements and the strain-temperature tests are compared in Table 3. We note that the M_s temperatures for the 51.5%Ni is consistently higher compared to the 50.8%Ni case using both the DSC and the strain-temperature measurement techniques. The austenite finish, A_f, temperature is slightly below room temperature for most cases producing a single crystalline cubic structure at room temperature.

Summary

The stress-strain response of aged NiTi alloys with two different Ni compositions is reported. It is noted that both NiTi compositions exhibit pseudoelastic deformation over an unusually high range of temperatures. Theoretical calculations of transformation strains have been undertaken in our previous study [2] and the result is provided in Table 1 as 4.38%. This is in close agreement with the experimental values obtained for the 50.8%Ni case. The transformation strains for the 51.5% Ni case are 2.5% which is lower than the theory. This difference can be explained based on the high volume fraction of precipitates which are untransformable. The results of the temperature cycling experiments were particularly insightful because they pointed out the transformation temperatures under stress and relative hysteresis in the two materials. The results in Figure 3 confirm that the material is in the fully austenitic state at room temperature and also that the hysteresis in the 50.8% case is significantly higher than the 51.5%Ni composition.

We note that the stress-strain response shown in Figure 2 does not exhibit a flat plateau region over which transformation occurs. Instead, the stress levels increase continuously during the transformation. This behavior has been observed in previous studies and point out the presence of multiple variants of martensite during transformation which mutually interact and increase the difficulty for further transformation. The complete reversibility of transformation was observed for the T=25°C (298K) cases and the T=167°C (440K) 51.5%Ni case. For the T= 167°C (440K) 50.8%Ni case the transformation is partially recoverable while it is fully recoverable for the 25°C (298K) case.

References

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TABLE 1

EXPERIMENTAL VALUES OF TRANSFORMATION STRAINS COMPARED WITH THE THEORETICAL VALUE IN [001] COMPRESSION

Material	Transformation strain, [001] Compression
NiTi	4.38%- Theoretical [1] (Type II-1 twinning)
51.5% at. Ni-Ti	2.5%- Experimental (Figure 3)
50.8% at. Ni- Ti	4.0%- Experimental (Figure 3)

TABLE 2

SUMMARY OF TRANSFORMATION TEMPERATURES FROM THE DSC MEASUREMENTS AND FROM THE STRAIN-TEMPERATURE RESPONSE UNDER STRESS

		M_s	M_f	A_s	A_f
DSC	51.5%Ni at.	-37°C	-51°C	11°C	25°C
	50.8%Ni	-55°C	-42°C	-7°C	2°C
Strain-Temperature Tests	51.5%Ni	-28°C	-47°C	-6°C	3°C
	50.8%Ni	-47°C	-65°C	-20°C	15°C

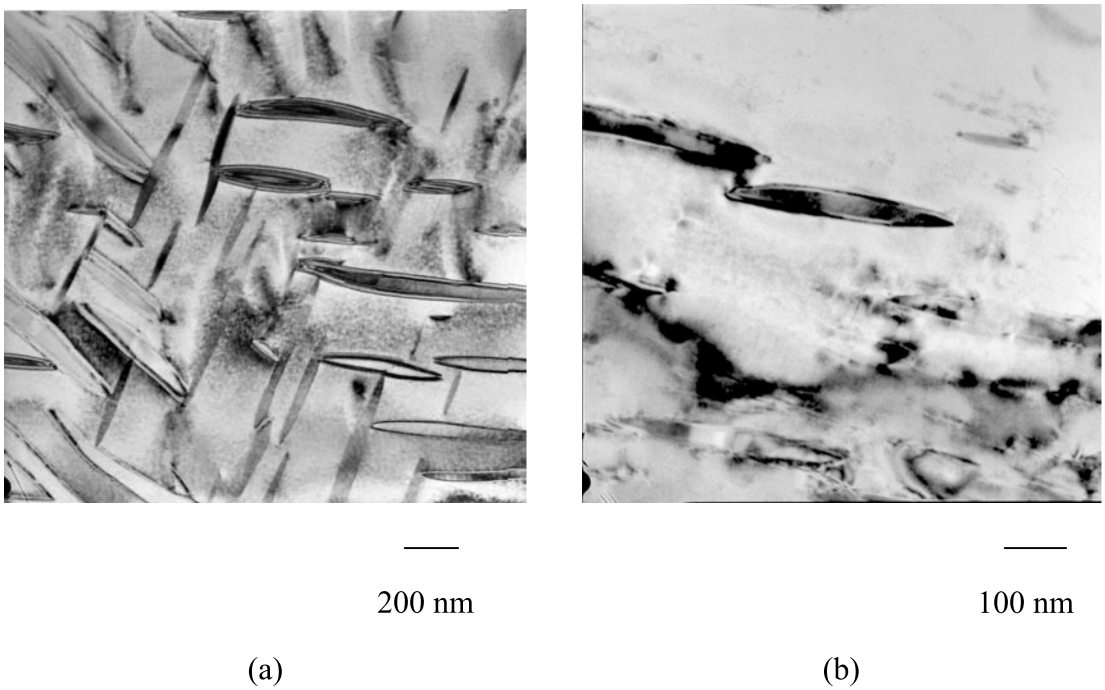

Figure 1: The Microstructure of the (a) 51.5% at. Ni and (b) 50.8% at. Ni NiTi alloys in the overaged state

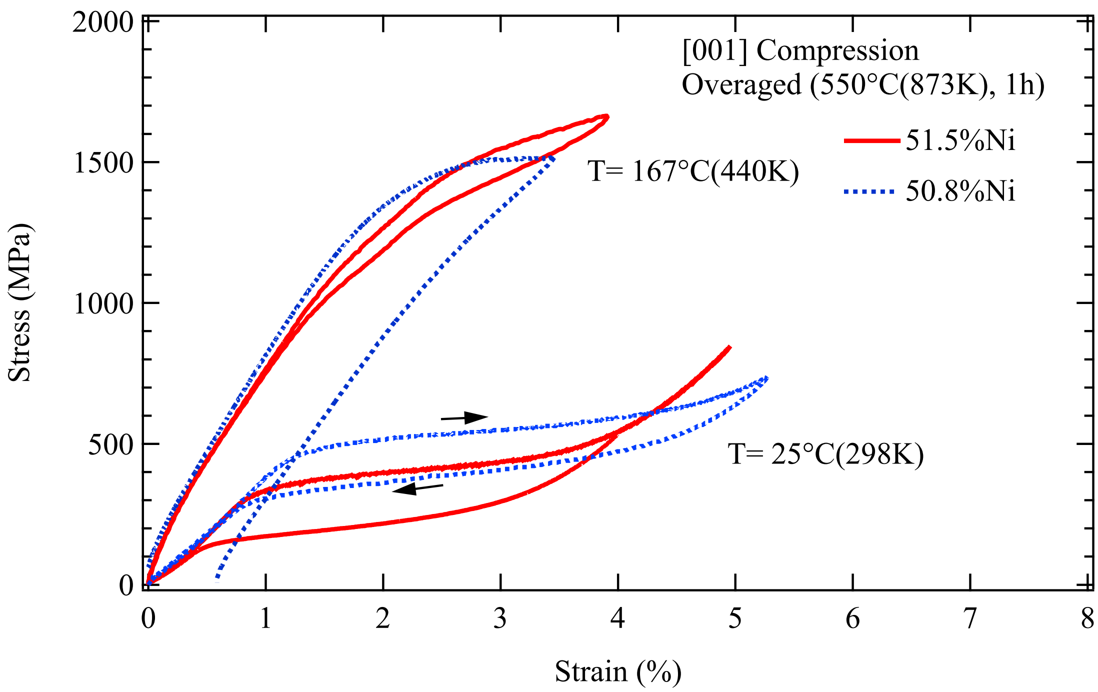

Figure 2: Compressive stress-strain response of 51.5% and 50.8Ni NiTi alloys at 25°C(298K) and 167°C(440K) in the [001] orientation.

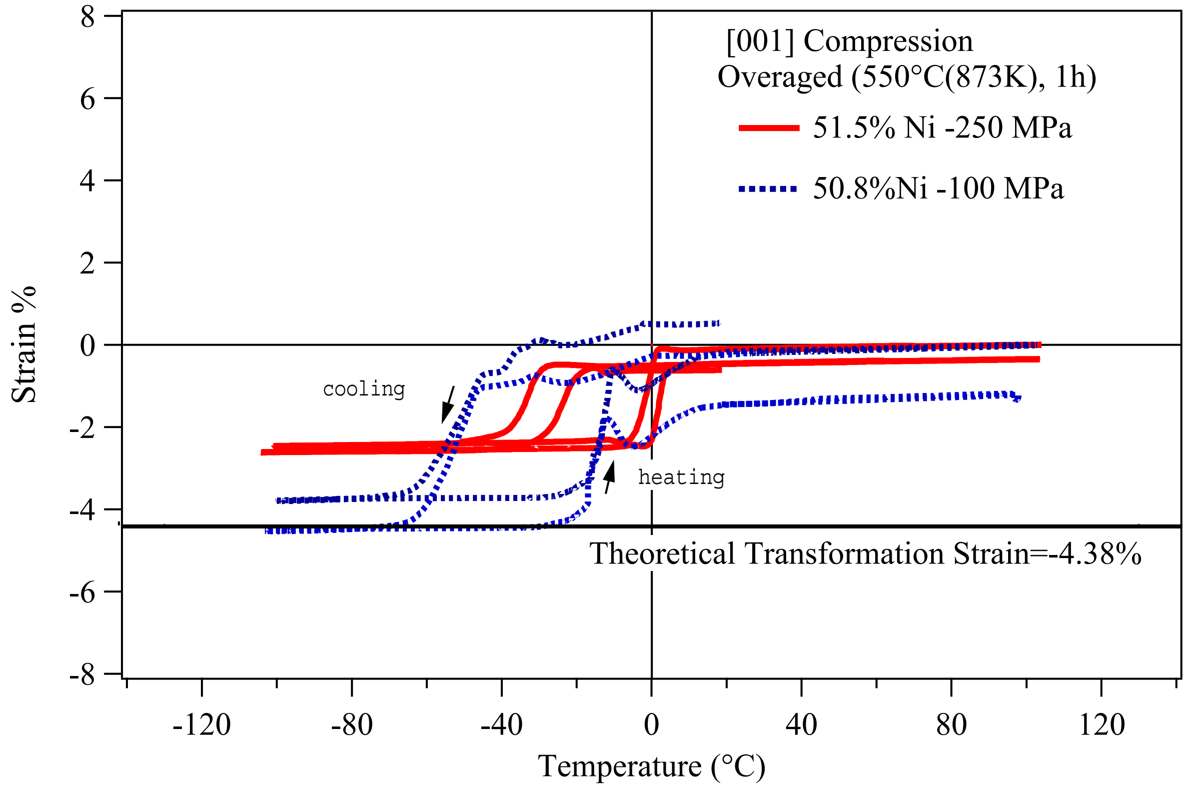

Figure 3: Strain-temperature behavior of two NiTi compositions under temperature cycling with a constant compressive stress.