# Hysteretic Behavior of Ferroelasticity of NiTi in Shear

Yinong Liu, D. Favier and L. Orgeas

*Journal of Intelligent Material Systems and Structures* 2006; 17; 1121
DOI: 10.1177/1045389X06065237

# Hysteretic Behavior of Ferroelasticity of NiTi in Shear

YINONG LIU,[1,]* D. FAVIER[2] AND L. ORGEAS[2]

[1]*School of Mechanical Engineering, University of Western Australia Crawley, WA6009, Australia*

[2]*Laboratory of Sols, Solids and Structures, URA CNRS 1511, Joseph Fourier University BP 53, 38041 Grenoble, CEDEX, France*

**ABSTRACT:** In the present work, the hysteretic behavior of ferroelastic deformation via martensite variant reorientation in a Ti–50.15 at.%Ni alloy is studied with cycling in shear. The stress hysteresis and the irreversible work dissipated during a cycle are found to decrease with cycling. The stress hysteresis is found to be dependent on the strain span of the loop but to be independent of the apparent strain about which the loop is performed. The mechanical hysteresis is attributed to two contributions: frictional resistance to twin boundary movement and matrix resistance to shape change of polycrystalline matrices.

*Key Words:* NiTi, shape memory alloys, martensitic transformation, mechanical behavior, hysteresis.

## INTRODUCTION

It is known that near-equiatomic NiTi alloys exhibit a variety of novel thermomechanical properties that are utilized in various applications, including the shape memory effect (SME), two-way memory effect (TWME), pseudoelastic (PE) behavior, and ferroelastic (FE) behavior. In the first three properties, the alloy always experiences a phase transformation cycle and may perform a mechanical work in the environment at a certain stage during the transformation cycle. In ferroelastic behavior, the alloy stays in a passive state and deforms only in response to the applied stress. Largely due to this reason, SME, TWME, and PE have received tremendous attention in research in the past few decades, but relatively less is known of the ferroelastic behavior of NiTi alloys.

The ferroelastic behavior of a NiTi shape memory alloy refers to the hysteretic deformation behavior of the alloy under the influence of an alternating external stress by a mechanism of reorientation of martensite variants. These variants are twin related and the reorientation process occurs by the movement of the twin boundaries between them. The hysteretic behavior of ferroelasticity in shape memory alloys is due to the irreversible energy being dissipated during the deformation process in overcoming the resistance to twin boundary movement. This deformation process usually takes place at a stress level much lower than the true yield strength of the martensite, owing to the high mobility of the twin boundaries. This renders the alloy with a remarkable ability to endure large non-elastic deformation without the risk of plastic deformation and, hence, strain hardening and fatigue. For this reason, an effort has been made in utilizing this property in applications such as dampers, cavitation damage resistant components, vibration absorbers, and flexible tools (Graesser and Cozzarelli, 1991; Saadat et al., 2002; Humbeeck, 2003).

In these applications, the shape memory component often experiences repeated cyclic transformation/deformation processes. It is known that transformation/deformation cycling changes the properties and transformation behavior of NiTi. Thus, the effects of various deformation/transformation cycling processes have long been the focus of research for many investigations. Most work to date has been performed in pseudoelasticity, due to the experimental simplicity associated with monodirectional loading and its interest in application. Compared to pseudoelastic cycling, the effect of ferroelastic cycling on the deformation behavior of shape memory alloys is largely ignored.

Another interest in studying the ferroelastic behavior of NiTi shape memory alloys is that it provides a much simpler condition under which the mechanisms of the hysteretic behavior of deformation can be studied, owing to the absence of complicity associated with phase transformations, as compared to the case of pseudoelasticity where the deformation behavior is dependent on the ambient temperature (Miyazaki et al., 1986;

*Author to whom correspondence should be addressed.
E-mail: liu@mech.uwa.edu.au



1045-389X/06/12 1121–6 $10.00/0 DOI: 10.1177/1045389X06065237

Shaw and Kyriakides, 1995) and the transformation heat (McCormick et al., 1993; Shaw and Kyriakides, 1995).

## EXPERIMENTAL PROCEDURE

The material used was a commercial Ti–50.15 at.%Ni alloy in sheet form. The as-received material was solution-treated at 1213 K for 1.8 ks followed by quenching into water at room temperature. The solution-treated sheet was cold rolled with 40% reduction in thickness to 0.8 mm prior to a final anneal treatment. Specimens of $30 \times 20 \times 0.8$ mm were cut from the sheet. The oxidation surfaces were removed using abrasive paper prior to testing. Ferroelastic deformation was performed in shear on an MTS DY35 universal mechanical testing machine. The machine was equipped with a liquid bath, which enabled the testing temperature to be controlled within an accuracy of 0.1 K (Manach and Favier, 1997). The specimens were cooled in liquid nitrogen prior to mechanical testing to ensure a full martensitic state. The ferroelastic cycling was performed at temperatures below the $A_s$ temperature of the specimens. The gage section of the shear was $3 \times 30$ mm and the shear direction was along the length of the specimen. The shear strain was measured at the grips using an LVDT. Deformation cycling was conducted between fixed end positions. The strain rate of the cycling was $1.7 \times 10^{-3}\,s^{-1}$. The shear stress was calculated from the measurement of the axial force, assuming a homogeneous stress state inside the gage section.

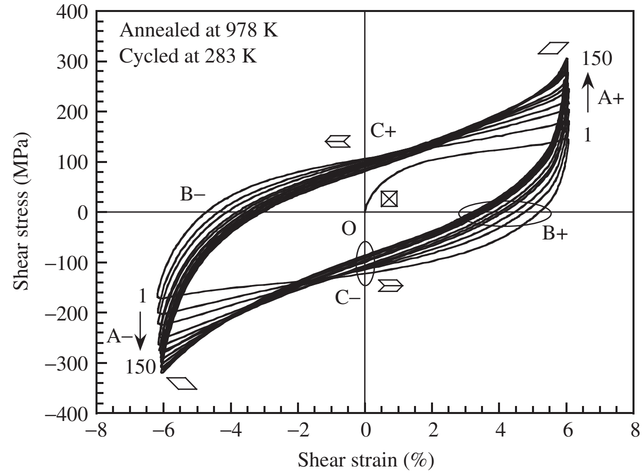


***Figure 1.*** *Shear stress–strain curves of ferroelastic cycling.*

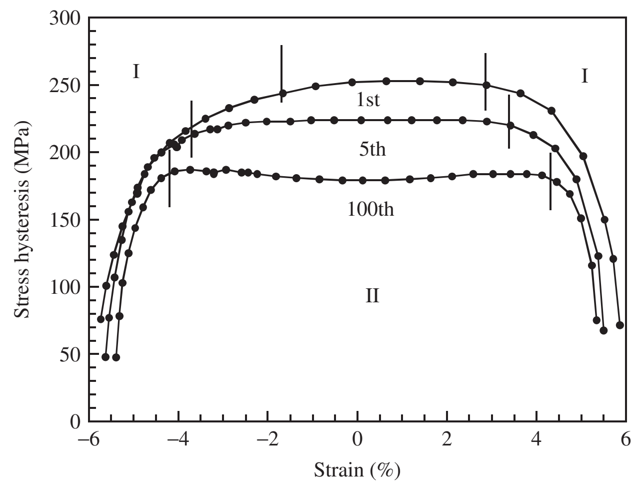


***Figure 2.*** *Mechanical hysteresis of ferroelasticity.*

## RESULTS

### Effect of Ferroelastic Cycling

Figure 1 shows shear stress–strain curves of a specimen cycled in martensitic state between +6 and −6% up to 150 cycles. The specimen was annealed at 984 K and the testing temperature was 283 K, 35 K below the $A_s$ temperature of the specimen. It is seen that the stress–strain curves of the ferroelastic hysteresis loops were highly symmetric in both directions. It is noted that the initial loading curve (OA+) appeared below the loading curve (A−B+C+A+) in the second cycle between 0 and 6% strain. This is apparently due to the difference in the martensite variant structure between O and C+ states, as schematically illustrated in the figure. The ferroelastic cycling was found to cause changes to the shape of the stress–strain loop. The stresses at the extremes A+ and A− of the loops increased progressively with cycling. The characteristic strains at the zero stress, labeled B− and B+ in the figure, shifted inward whereas the absolute values of the characteristic stress at the zero strain, labeled C− and C+, decreased, resulting in a decrease in stress hysteresis. After 100 cycles, the ferroelastic loop became highly repeatable.

Figure 2 shows the stress hysteresis profiles of three ferroelastic loops, i.e., for the 1st, 5th, and 100th cycles. The hysteresis is measured as the difference between the positive stress and the negative stress at each given apparent strain level along the strain span of the loop. It is seen that the stress hysteresis profile exhibited a downward 'U' shape. The profile may be regarded in two regimes, regime I at the extremities of the hysteresis loop where the hysteresis increased progressively and regime II in the middle section where the hysteresis appeared relatively constant, as tentatively indicated by the short vertical indicator bars on the curves. The transition from regime I to regime II was found to shift progressively outwards and toward the extremities of the loop with cycling.

Figure 3 shows the evolution of stress hysteresis, $\eta_\sigma$, and the energy dissipation, $\Delta W$, during cycling.

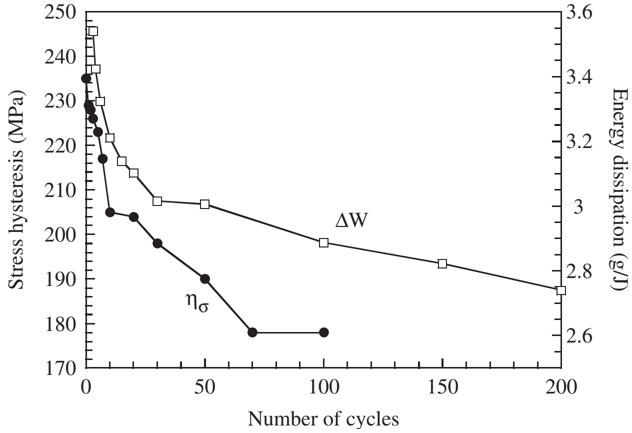


***Figure 3.*** *Effect of ferroelastic cycling on stress hysteresis and energy dissipation.*

The stress hysteresis is measured at the zero apparent strain and the energy dissipation is the integrated area enclosed within each hysteretic cycle. It is obvious that the magnitude of $\Delta W$ is not a material constant and is directly dependent on the strain span, i.e., the strain difference between the two extremes of a hysteresis loop. Both parameters were found to decrease continuously with the increasing number of cycles. The hysteresis decreased from 235 to 178 MPa after 100 cycles, i.e., by ~25%. The energy dissipation for a full cycle of ±6% decreased from 3.54 to 2.89 J/g after 100 cycles, by 18%.

## Effect of Strain Span

Figure 4 shows partial ferroelastic cycles of different strain spans of a specimen annealed at 720 K. The testing temperature was 268 K, ~30 K below its $A_s$ temperature. The ferroelastic cycles shown in the figure were measured after 100 cycles to ±9% strain when the changes in the stress–strain behavior became stabilized. Between each partial loop cycling shown in the figure, a full loop cycle was conducted so that each partial loop was measured under similar conditions. For each partial loop cycling, two cycles were performed and the second cycle was recorded, so that the conditions at each turning point in the figure were identical to those at the reciprocal point on the opposite deformation side for each partial loop. All the partial loops appeared symmetric and were confined within the major loop, except the smallest one at ±1% strain span, which is apparently asymmetrical to the central point.

Figure 5 shows the hysteresis curves for the ferroelastic loops shown in Figure 4. It is seen that the hysteresis curves of smaller strain spans were always enveloped by those of larger strain spans. Similar to Figure 2, the two dashed lines indicate transition from regime I to regime II. It is seen that the strain

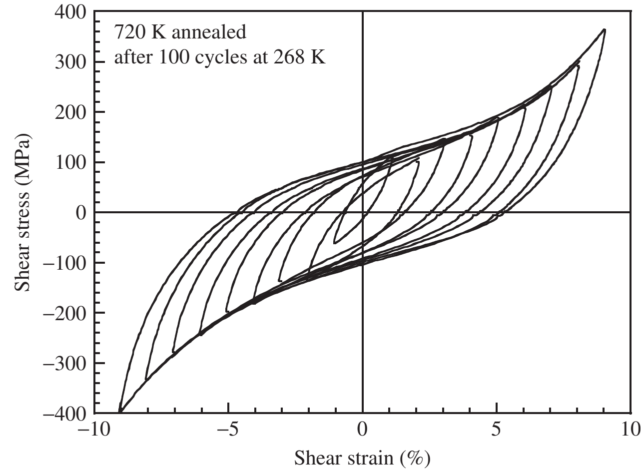


***Figure 4.*** *Partial ferroelastic hysteresis loops of different strain spans.*

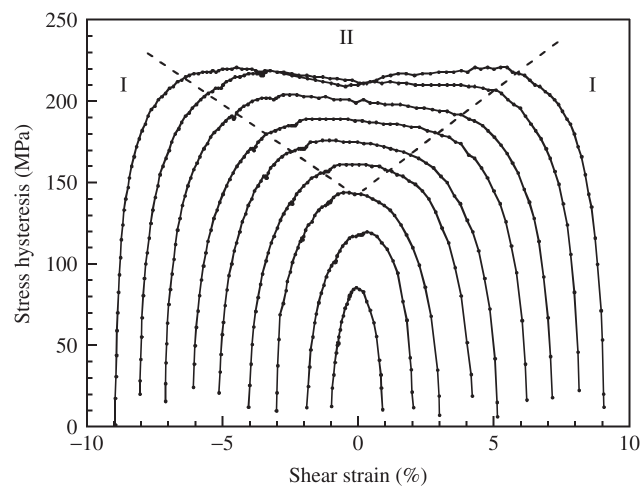


***Figure 5.*** *Mechanical hysteresis of partial ferroelastic loops.*

span of hysteresis plateau in regime II increased proportionately with increase in the total strain span of the hysteresis loop. For the stress–strain loops of strain spans smaller than ±3%, regime II disappeared.

Figure 6 shows the hysteresis measured at zero strain and the energy dissipation for all the subloops as functions of the strain span. It is seen that the stress hysteresis increased progressively with the increasing strain span of the ferroelastic loops. There appeared to be an almost linear section between the stress hysteresis and the strain span for the hysteresis loops of strain spans larger than 6% (or ±3%). The deviation from the apparent linearity of the three data points for hysteresis loops of small strain spans is obviously due to the absence of the hysteresis plateau in their hysteresis profile, as shown in Figure 5. In other words, the total strain spans were too small to allow the full realization of the mechanical hysteresis. The energy dissipation also increased with increasing strain span, as expected.

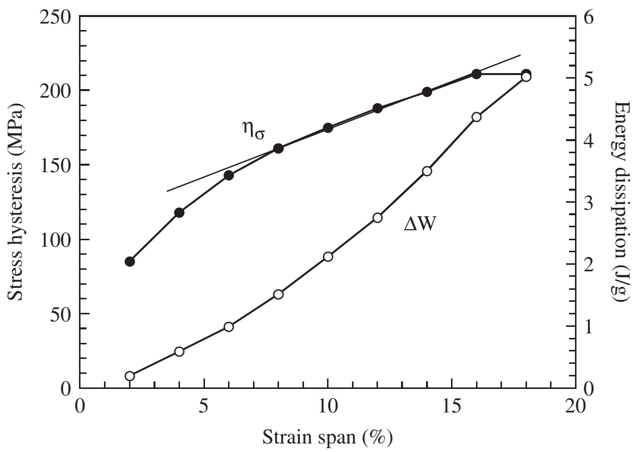


***Figure 6.*** *Dependence of stress hysteresis and energy dissipation on the strain span of ferroelastic cycles.*

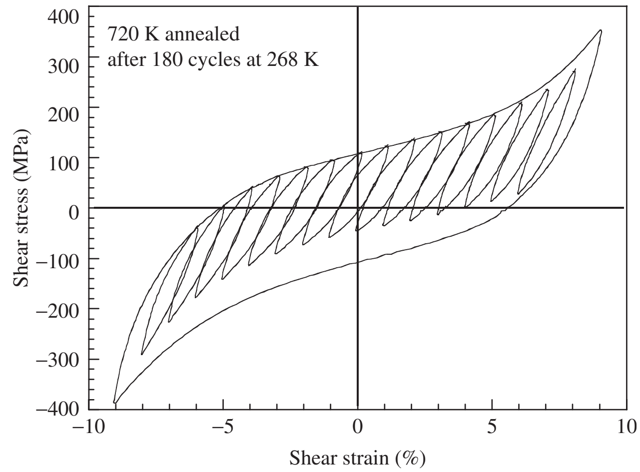


***Figure 7.*** *Partial cycling at different apparent strains.*

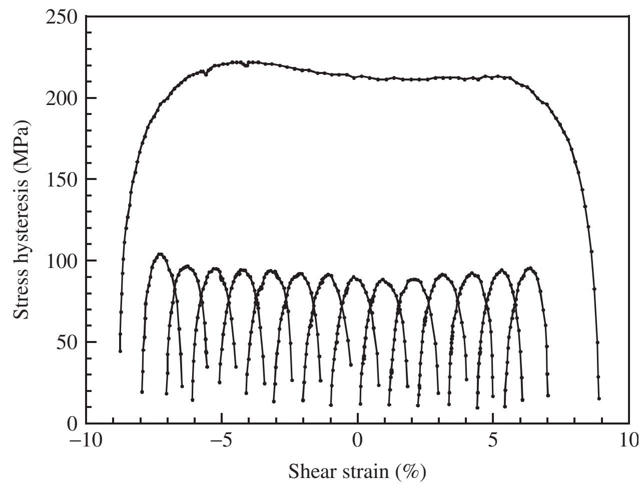


***Figure 8.*** *Stress hysteresis of partial ferroelastic loops at different apparent strain positions.*

## Effect of Strain Position

Figure 7 shows the measurements of minor hysteresis loops on a fixed strain span of 2% at different apparent strain positions on the major hysteresis loop. Similar to the experiment shown in Figure 4, a major loop was performed between each minor loop measurement. After each major loop, two minor loop cycles were performed and the second one was recorded. All the minor loops were performed by returning from the upper branch of the major loop. This actually covered both situations where a minor loop started from incomplete loading on the positive strain side and where a minor loop started from incomplete unloading on the negative strain side.

Figure 8 shows the hysteresis curves of the minor loops in comparison with the hysteresis curve of a major loop. It is evident that the maximum stress hysteresis of the minor loops was independent of their relative positions on the major hysteresis loop, constant at ~90 MPa.

## DISCUSSION

### Martensite Reorientation in Polycrystalline Matrix

Ferroelastic behavior of NiTi shape memory alloys is associated with the martensite reorientation process. Twin-related martensite variants reorient by twinning at a certain stress. The reverse twinning of the oriented martensite may be induced by reversing the direction of the external stress; thus forming a hysteresis loop. The actual variant structure at any stage of the deformation cycle is dependent on the preceding state of deformation as well as the apparent strain level, as indicated in Figure 1, with '⊠' representing the self-accommodating thermal martensite, '▱' representing the oriented state of the martensite, and '⋙' representing the structure of the martensite at zero apparent strain returning from a fully oriented state. Apparently, the difference between the initial loading curve (OA+) and the curve in the first quadrant (C+A+) of the subsequent ferroelastic cycles is attributed to the difference in the variant accommodation structure.

It is commonly perceived that martensite reorientation occurs without plastic deformation, due to the fact that the critical stress for reorientation is usually much lower than the yield strength of martensite and that the deformation is usually totally recoverable upon heating. However, it has been demonstrated that reorientation deformation causes internal plastic deformation, as evidenced by the increased dislocation density observed under transmission electron microscope (Xie et al., 1998; Liu et al., 2000). It is also observed that a simple tensile deformation by martensite reorientation is effective in establishing a two-way memory effect in polycrystalline NiTi (Liu et al., 1999). This is indicative of an internal plastic deformation.

The occurrence of the internal plastic deformation is, in fact, an essential requirement for the reorientation deformation in a polycrystalline matrix (Liu and Favier, 2000; Jourdan et al., 1999). It is known that the deformation by martensite reorientation proceeds by the coalescence of variants to form a dominant variant of the preferential orientation relative to the external stress in each grain (Miyazaki et al., 1989a, b). An external deformation is realized by accumulating the internal microstrains produced by each preferentially oriented dominant variant in each austenitic grain. Due to the difference in crystallographic orientation between neighboring austenitic grains, these preferential variants exhibit orientation mismatches, or microstrain discontinuity, at grain boundaries. Therefore, internal plastic deformation is required to operate within the matrix to co-ordinate the discontinuity of the microstrains of the preferential variants in order to maintain the integrity of the matrix. In this regard, the polycrystalline matrix of NiTi has been modeled as a composite structure comprising two distinctive regions: the grain interior which is capable of martensite crystallographic reorientation and a grain-affected region which is incapable of reorientation deformation and thus experiences plastic deformation during the processes of martensite reorientation (Liu et al., 2004).

## Mechanical Hysteresis

In light of the above discussion, it is recognized that there exist two possible sources of frictional resistance to deformation via martensite reorientation in a polycrystalline matrix: the frictional resistance to the movement of twin boundaries and the matrix resistance to shape change. Whereas the contribution of the frictional resistance to twin boundary movement to ferroelastic hysteresis is commonly understood, the contribution of the matrix resistance to global shape change has not been properly recognized in the literature. The concept of this resistance to deformation may be explained as follows.

1. Should this resistance be zero in the matrix, a gentle touch to exert an infinitesimal stress would be expected to be able to induce a full stress-induced martensitic transformation in a polycrystalline sample at just above the $M_s$ temperature, when the thermodynamic resistance (including that due to transformation interface friction) is zero; however, this is never the case.
2. Imagining that the martensite variants are toy building blocks packed in carton boxes, which mimic the function of grain boundaries and that the blocks are perfectly lubricated so they can slide with respect to each other with no friction, then a finite mechanical force is still needed to deform the complete array of the boxes via the mechanism of block sliding, simply due to the mismatch in sliding direction of the blocks in neighboring boxes.

The frictional resistance to twin boundary movement is determined by the metallurgical conditions of the matrix as well as the reorientation crystallography, which may be regarded as a material constant (for a given sample in a particular deformation cycle). This resistance is experienced by a thermally induced transformation as well as a mechanically induced transformation. The matrix resistance to shape change, which is not experienced in a thermally induced transformation but experienced only in a stress-induced transformation or stress-induced martensite reorientation, i.e., where a global deformation is involved, is dependent on the magnitude and mode of deformation as well as the metallurgical conditions of the matrix, such as grain size, texture, and dislocation density. The measurement of stress hysteresis is an accumulated effect, in the direction of the external stress, of all microscopic internal resistive forces. Thus, the magnitude of stress hysteresis of ferroelastic deformation may be expressed as:

$$\tau = \tau_{\rm d}(\gamma, \Delta\gamma) + \phi(\gamma)\tau_{\rm t} \quad (1)$$

where $\tau_{\rm d}(\gamma, \Delta\gamma)$ is the resistance to matrix shape deformation, $\tau_{\rm t}$ is the frictional resistance to twin boundary movement, and $\phi(\gamma)$ is an averaged orientation factor that resolves the critical shear stresses for twinning on individual twinning planes into the external shear stress. Based on the concept that some variants will collectively reorient more easily at lower stresses at earlier stages of ferroelastic deformation than others, $\phi(\gamma)$ is considered a function of the total strain. Obviously, $\phi(\gamma)$ is also a function of the texture of a sample and affected by the mode of deformation. This is neglected in the formulation of Equation (1) for the reason of simplicity in this discussion, which is concerned with the evolution of the hyteresis of one given material. $\tau_{\rm d}(\gamma, \Delta\gamma)$ is considered a function of the magnitude of deformation from any reference point ($\Delta\gamma$) and the apparent strain ($\gamma$), and is dependent on the stress-state, mode of deformation and specimen geometry. Considering that different martensite variants reorient selectively at different global stress levels according to orientations relative to the preferential variant, $\phi(\gamma)$ is regarded to vary with the degree of reorientation, i.e., the strain of the ferroelastic deformation ($\gamma$). Based on this understanding, it is obvious that the critical stress, hence the stress hysteresis, increases with the degree of deformation, as demonstrated experimentally in Figure 6. Such dependence, being of a mechanical nature, is also expected to be applicable to pseudoelastic deformation (Orgeas et al., 1997).

Notably, it is often reported in the literature that deformation via martensite reorientation occurs over a stress plateau, exhibiting Lüders-type behavior (Liu et al., 1998). In this case the accumulation of the total strain is achieved by the propagation of a deformation band of reoriented martensite. The local situation at the moving interface between the region of reoriented martensite and the region of the self-accommodating martensite remains unchanged throughout the deformation process. This means that the critical stress required to propagate the deformation band remains constant. Obviously, the apparent independence of the stress hysteresis to strain is an artifact (Liu et al., 1999).

### Effect of Mechanical Cycling

Ferroelastic cycling was found to decrease both the stress hysteresis and the irreversible energy dissipated in a ferroelastic cycle. This is attributed to the production of internal plastic deformation in repeated cycles, as discussed above. This may be expressed in parameter $\tau_d(\gamma,\Delta\gamma)$ in Equation (1). It is seen in Figure 1 that the critical stress for martensite reorientation built up progressively at the extremities of the ferroelastic loop during cycling, whereas it decreased at the zero apparent strain. This seems to suggest that the cycling has a 'cleaning up' effect as opposed to a 'building-up' effect for the internal defects generated during the cycling. Such a behavior is desirable for applications where repeated deformation is required with minimum strain hardening.

## CONCLUSIONS

1. Ferroelastic cycling via martensite reorientation in polycrystalline NiTi causes reduction in both mechanical hysteresis and mechanical energy dissipation capacity. This is attributable to the modification of the microstructure due to internal plastic deformation associated with martensite reorientation in polycrystalline NiTi.
2. The stress hysteresis of ferroelastic deformation is attributable to two main contributions viz., the frictional resistance to twin boundary movement and the mechanical resistance of the polycrystalline matrix to global shape change. The matrix resistance to deformation is expected to vary as a result of mechanical cycling.
3. The stress hysteresis of a ferroelastic cycle is dependent on the strain span of the ferroelastic loop, at least within the strain range for martensite reorientation. The stress hysteresis of a ferroelastic cycle is independent of the apparent strain level about which the loop is performed.

## REFERENCES

Graesser, E.J. and Cozzarelli, F.A. 1991. "Shape-memory Alloys as New Materials for Aseismic Isolation," *J. of Eng. Mechanics*, 117:2590–2608.

Jourdan, C., Gastaldi, J., Baronnet, A., Belkahla, S. and Guenin, G. 1999. "*In Situ* Study by Synchrotron X-ray Diffraction of the Motion of Basal Stacking Faults During the Reverse-phase Transformation of a Cu-Zn-Al Single Crystal," *Mater. Sci. & Eng. A*, 266(1–2):191–197.

Liu, Y. and Favier, D. 2000. "Stabilisation of Martensite due to Cold Deformation via Martensite Reorientation in NiTi," *Acta Materialia*, 48(13):3489–3499.

Liu, Y., Liu Y. and Van Humbeeck, J. 1998. "Lüders-like Deformation Associated with Martensite Reorientation in NiTi, *Scripta Materialia*, 39(8):1047–1055.

Liu, Y., Houver, I., Xiang, H., Bataillard, L. and Miyazaki, S. 1999. "Strain-dependence of Pseudoelastic Hysteresis of NiTi," *Metallurgical and Materials Transactions A*, 30(5):1275–1282.

Liu, Y., Liu Y. and Van Humbeeck, J. 1999. "Two-way Shape Memory Effect Developed by Martensite Deformation in NiTi," *Acta Mater.*, 47(1):199–209.

Liu, Y., Xie, Z., Van Humbeeck, J., Delaey, L. and Liu, Y. 2000. "On the Deformation of the Twinned Domain in NiTi Shape Memory Alloys," *Phil. Mag. A*, 80:1935–1953.

Liu, Y., Favier, D. and Orgeas, L. 2004. "Mechanistic Modelling of Thermoelastic Martensitic Transformation in NiTi," *J. de Phys. IV*, 115:37–45.

Manach, P. and Favier, D. 1997. "Shear and Tensile Thermomechanical Behaviour of Near Equiatomic NiTi Alloy," *Mater. Sci. & Eng. A*, 222(1):45–57.

McCormick, P.G., Liu, Y. and Miyazaki, S. 1993. "Intrinsic Thermal-mechanical Behaviour Associated with the Stress-induced Martensitic Transformation in NiTi," *Mater. Sci. & Eng. A*, 167(1–2):51–56.

Miyazaki, S., Imai, T., Igo, Y. and Otsuka, K. 1986. "Effect of Cyclic Deformation on the Pseudoelasticity Characteristics of Titanium-nickel Alloys," *Metall. Trans. A*, 17:115–120.

Miyazaki, S., Otsuka, K. and Wayman, C.M. 1989a. "The Shape Memory Mechanism Associated with the Martensitic Transformation in Titanium-nickel Alloys. I. Self-accommodation," *Acta Metall.*, 37(7):1873–1884.

Miyazaki, S., Otsuka, K. and Wayman, C.M. 1989b. "The Shape Memory Mechanism Associated with the Martensitic Transformation in Titanium-nickel Alloys. II. Variant Coalescence and Shape Recovery," *Acta Metall.*, 37(7):1885–1890.

Orgeas, L., Liu, Y. and Favier, D. 1997. "Experimental Study of Mechanical Hysteresis of NiTi during Ferroelastic and Superelastic Deformation," *J. de Phys. IV*, 7(C5):477–482.

Saadat, S., Salichs, J., Noori, M., Hou, Z., Davoodi, H., Bar-on, I., Susuki, Y. and Masuda, A. 2002. "An Overview of Vibration and Seismic Applications of NiTi Shape Memory Alloy," *Smart Mater. Struct.*, 11:218–229.

Shaw, J.A. and Kyriakides, S. 1995. "Thermomechanical Aspects of NiTi," *J. Mech. Phys. Solids*, 43(8):1243–1281.

Van Humbeeck, J. 2003. "Damping Capacity of Thermoelastic Martensite in Shape Memory Alloys," *J. Alloys and Compounds*, 355(1):58–64.

Xie, Z., Liu, Y. and Van Humbeeck, J. 1998. "Microstructure of NiTi Shape Memory Alloy due to Tension-compression Cyclic Deformation," *Acta Mater.*, 46(12):1989–2000.