Journal of Intelligent Material Systems and Structures
http://jim.sagepub.com/

Pseudoelastic Hysteresis in Martensitic Reorientation of Cu-Zn-Al Polycrystalline Shape Memory Alloys

W. -Y. Yan, Q. -P. Sun and K. -C. Hwang

Journal of Intelligent Material Systems and Structures 1996 7: 114
DOI: 10.1177/1045389X9600700113

phases. A simpler form of the popular Tanaka model was presented. It was illustrated that a model by Ivshin and Pence, which uses a Reuss formulation, yields nearly identical results when both models were used with the same kinetic law. The cause of these results is a natural and common (to these and other constitutive models) separation of the total strain into the sum of elastic and transformation components. Then, since the transformation strain overwhelms the material response, the finer details of the mechanical portion of the constitutive law are lost.

One implication of these simple results is that when choosing a model for 1-D SMA material behavior, the simplest (or your "favorite") constitutive law will likely perform an adequate job. The most important concern is the use of a kinetic law which can adequately represent the material behavior in anticipated application conditions. An accurate kinetic law used within a variety of constitutive laws should produce nearly indistinguishable results.

Note that the results indicated here are not applicable to more micro-scaled constitutive laws or other constitutive models where the kinetics are not clearly separable from the stress-strain relations. For example, Patoor (Patoor, Eberhardt and Berveiller, 1994) has developed a micro-macro scale constitutive law based on energetic considerations for all possible 24 martensitic variants and the austenitic phase. These are combined in a self-consistent type model to first predict single crystal behavior and then at yet another level are combined and averaged to provide polycrystalline behavior by considering an assemblage of grains. Within such a unified constitutive model, the transformation kinetics and stress-strain relation are inextricably intertwined and one cannot state that only the "transformation kinetics description" is critical. As with the Boyd-Lagoudas model, Patoor's work also provides a three-dimensional material description.

ACKNOWLEDGEMENTS

The authors wish to acknowledge support of this work through a grant by the National Science Foundation (MSS-9308937).

REFERENCES

Boyd, J. G. and D. C. Lagoudas. 1994. "Thermomechanical Response of Shape Memory Composites", *J. Intell. Matl. Syst. & Struct.*, 5:333-346.

Boyd, J. G. and D. C. Lagoudas. 1995. "A Thermodynamic Constitutive Model for the Shape Memory Materials. Part I. The Monolithic Shape Memory Alloys", *to appear in Int. J. Plas.*

Brinson, L. C. 1993. "One Dimensional Constitutive Behavior of Shape Memory Alloys: Thermomechanical Derivation with Non-Constant Material Functions", *J. of Intell. Mat. Syst. & Struct.*, 4(2):229-242.

Brinson, L. C. and R. Lammering. 1993. "Finite Element Analysis of the Behavior of Shape Memory Alloys and their Applications", *Int. J. Solids & Struct.*, 30(23):3261-3280.

Delaey, L. 1991. "Diffusionless Transformations," in *Phase Transformations in Materials.* E. P. Haasen, Ed., Weinheim, pp. 341-402.

Funakubo, H., Ed. 1987. *Shape Memory Alloys,* translated from the Japanese by J. B. Kennedy, New York: Gordon and Breach Science Publishers.

Ivshin, Y. and T. J. Pence. 1994. "A Constitutive Model for Hysteretic Phase Transition Behavior", *Int. J. Eng. Sci.*, 32:681-704.

Ivshin, Y. and T. J. Pence. 1994. "A Thermomechanical Model for a One Variant Shape Memory Material", *J. Intell. Matl. Syst. & Struct.*, 5:455-473.

Liang, C. and C. A. Rogers. 1990. "One-Dimensional Thermomechanical Constitutive Relations for Shape Memory Materials", *J. of Intell. Mater. Syst. and Struct.*, 1(2):207-234.

Patoor, E., A. Eberhardt and M. Berveiller. 1988. "Thermomechanical Behavior of Shape Memory Alloys", *Arch. Mech. (Warszawa)*, 40:775-794.

Patoor, E., A. Eberhardt and M. Berveiller. 1994. "Micromechanical Modelling of the Shape Memory Behavior", *ASME International Congress and Exposition,* Chicago, ASME, Proceedings of the Symposium on Phase Transformations and Shape Memory Alloys, AMD-Vol. 189, L. C. Brinson and B. Moran, Eds., pp. 23-37.

Pence, T. J. 1994. "A Macroscopic Model for Thermoelastic Hysteresis in Shape-Memory Materials", *ASME International Congress and Exposition,* Chicago, ASME, Proceedings of the Symposium on Phase Transformations and Shape Memory Alloys, AMD-Vol. 189, L. C. Brinson and B. Moran, Eds. pp. 45-58.

Sato, Y. and K. Takana. 1988. "Estimation of Energy Dissipation in Alloys due to Stress-Induced Martensitic Transformation", *Res Mechanica*, 23:381-393.

Tanaka, K. 1986. "A Thermomechanical Sketch of Shape Memory Effect: One Dimensional Tensile Behavior", *Res Mech.*, 18:251-263.

Tanaka, K. and R. Iwasaki. 1985. "A Phenomenological Theory of Transformation Superplasticity", *Eng. Fract. Mech.*, 21(4):709-720.

Tanaka, K., S. Kobayashi and Y. Sato. 1986. "Thermomechanics of Transformation Pseudoelasticity and Shape Memory Effect in Alloys", *Int. J. Plast.*, 2:59-72.

Tanaka, K. and S. Nagaki. 1982. "A Thermomechanical Description of Materials with Internal Variables in the Process of Phase Transitions", *Ing. Arch.*, 51:287-299.

Pseudoelastic Hysteresis in Martensitic Reorientation of Cu-Zn-Al Polycrystalline Shape Memory Alloys

W.-Y. YAN, Q.-P. SUN* AND K.-C. HWANG
Department of Engineering Mechanics
Tsinghua University
Beijing 100084, P. R. China

ABSTRACT: The stress-induced martensitic reorientation of two kinds of Cu-Zn-Al polycrystalline shape memory alloys were studied through experiment. Special attention was paid to the deformation behavior of these polycrystals during the reorientation. Experimental result indicates that for the two materials after reorientation the deformation is pseudoelastic as long as applied stress is smaller than the prestress that induced the reorientation. Detailed research on the pseudoelastic hysteresis was performed. The experimental phenomena are very similar to that of the pseudoelasticity of shape memory alloys due to the forward and reverse martensitic transformations at high temperature.

---

*Author to whom correspondence should be addressed.

INTRODUCTION

SHAPE memory alloys, abbreviated to SMA, are known for two very important behaviors: pseudoelasticity and shape memory effect. At high temperature $T > A_f$, the temperature at which the reverse transformation from martensite to austenite is completed under no stress, the forward transformation from austenite to martensite can be induced by applied force with the shape change of the material. If the applied force is removed, the reverse transformation from martensite to austenite happens and the shape of the material recovers. This behavior is called pseudoelasticity. On the other hand, if temperature T is lower than M_f, the temperature at which the forward transformation from austenite to martensite is completed under no stress, martensite is a stable phase. When force is applied on a SMA specimen, the martensite will reorientate between different martensite variants. Then if the external force is removed, the strain due to the reorientation no longer recovers. There will exist residual deformation. But if we heat the transformed material, the residual deformation will disappear and the shape of the material will recover. This is called shape memory effect. These two important behaviors exhibited by shape memory alloys have been extensively applied in many fields.

In the last twenty years, physicists, material scientists and mechanics researchers, based on their own fields respectively, have been engaged in theoretical and experimental researches on the constitutive behavior of shape memory alloys. A series of achievements are obtained, see references Delaey et al. (1974), Otsuka and Shimizu (1986), Sun and Hwang (1993, 1994), etc. However there are still many problems and phenomena needed to be solved and discovered. Recently, J. Ortin (1992) has experimentally studied the pseudoelastic hysteresis of a Cu-Zn-Al monocrystalline SMA due to the stress-induced forward and reverse martensitic transformation at room temperature. The stress-strain trajectories he obtained have two basic characters:

1. The stress-strain trajectories depend on the loading history, or we can say, the trajectories depend on the sequence of previous inversion loading points, which the system happens to memorize.
2. The memory of a previous inversion point is erased when the trajectory runs over the given point again.

Here inversion loading means the change from loading to unloading or from unloading to loading.

We have measured the pseudoelastic stress-strain curve of a Cu-Zn-Al polycrystalline SMA at room temperature T_r, $T_r > A_f$. The experimental conclusion is exactly the same as that J. Ortin obtained on Cu-Zn-Al monocrystalline SMA. Some results are shown in Figure 1.

Now we focus our study on another two kinds of Cu-Zn-Al polycrystals. Their characteristic temperature M_f is higher than room temperature T_r. Thus, the material is in

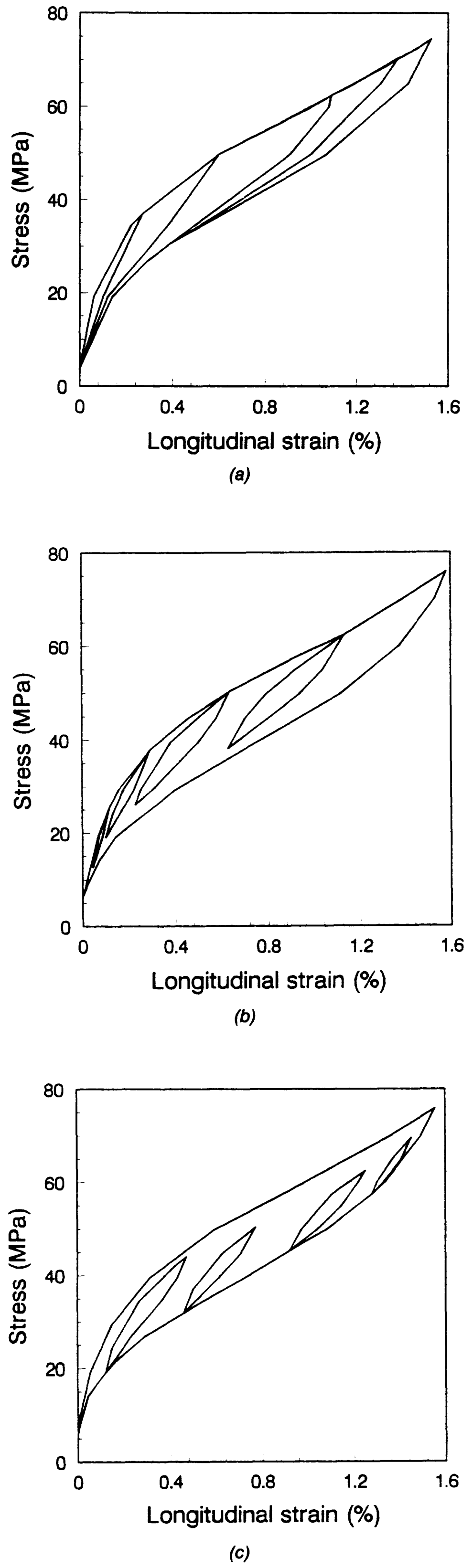

Figure 1. ***Pseudoelastic hysteresis exhibited by a Cu-26Zn-4Al (wt %) polycrystalline SMA under uniaxial tension at room temperature: (a) completely unloading at different loading step; (b) unloading-loading cycles at different loading step; (c) loading-unloading cycles at different unloading step.***

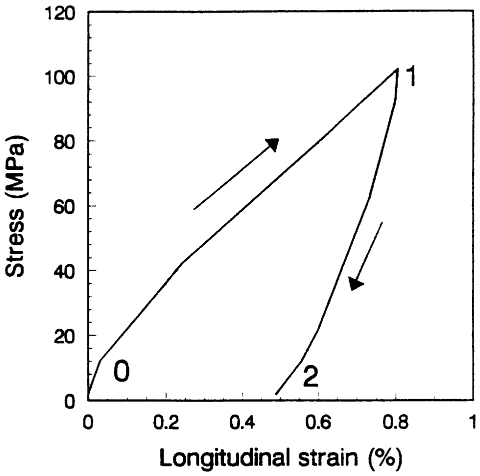

Figure 2. *Stress-strain curve of SMA2 under uniaxial compression measured by strain gauge at room temperature.*

martensitic phase at room temperature and martensite reorientation will take place under external force. After unloading, the strain due to the reorientation will not recover, the material has residual deformation, as showed in Figure 2. This character is similar to the plastic deformation of common metals. For common metal, after plastic deformation, the material is hardened. The new yield stress is the previously applied largest stress. Now, considering the intelligent material shape memory alloy, what is its deformation behavior after martensitic reorientation? Is its deformation behavior still similar to that of common metals? This is what we study experimentally in this paper.

EXPERIMENT

We have chosen two kinds of material. They are Cu-25Zn-4Al (wt %), represented by SMA1, and Cu-25.5Zn-4Al (wt %), represented by SMA2. Their M_f is higher than room temperature. These alloys were prepared from weighted amounts of the raw materials with purities of 99.9% for Cu, Zn and Al by melting in a intermediate frequency induction furnace at 1100°C. Then they were annealed for 4 hours at 850°C for homogenization. The samples from these alloys were experimented under two kinds of loading condition, i.e., uniaxial tension and uniaxial compression.

All experiments were performed at room temperature in a strain-controlled SHIMAZU test machine. The deformations of the tensile specimens were measured by a 25 mm gauge length extensometer. The deformations of the compression specimens were measured by a 10 mm gauge length extensometer. Because the size of the crystals of SMA2 is relatively small (<0.3 mm), foil strain gauges with area of 2 mm × 3 mm were also used to measure the longitudinal strains and transverse strains of SMA2 specimens. The results obtained by extensometer are the total average deformations of specimens while the results obtained by foil strain gauges are the local strains of specimens. As we will show later the experimental results are coincident at different loading condition with different measuring methods. We must point out here that it is not useful to quantitatively compare the longitudinal strain with the transverse strain because the measured positions of the longitudinal strain gauge and the transverse strain gauge are not coincident.

In order to use a specimen repeatedly, it was heated until its temperature was higher than its A_f after each test was finished. Then it was cooled to room temperature and used again. Certainly, because of the instability of SMA and experimental error, repeating test will create deviation in test result. This deviation is not what we want to study and is neglected here.

EXPERIMENT RESULT

Figure 3 shows the stress-strain curve of SMA2 under compression measured by strain gauge at room temperature. During the loading process 0 → 1, martensitic reorientation takes place and it induces large deformation. Then unloading 1 → 2, there exists residual strain. Now reloading, from Figure 3, we can see the stress-strain curve no long returns along the unloading path. When the force reaches the initial unloading value, the curve reaches the initial unloading point also. This indicates that the deformation of the material after reorientation is not real elastic but pseudoelastic. The phenomenon is no longer similar to the plastic deformation of common metal material. It is similar to that of the pseudoelasticity behavior of shape memory alloy at high temperature ($T_{test} > A_f$). Obviously, the pseudoelastic hysteretic loop is completely determined by the unloading Point 1. In Figure 4, if we continue loading the specimen after external force reaches the initial unloading value, the stress-strain curve proceeds along the

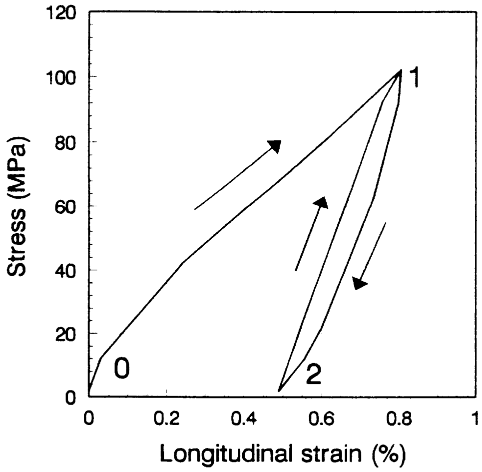

Figure 3. *Pseudoelastic hysteretic loop of SMA2 under compression after martensitic reorientation.*

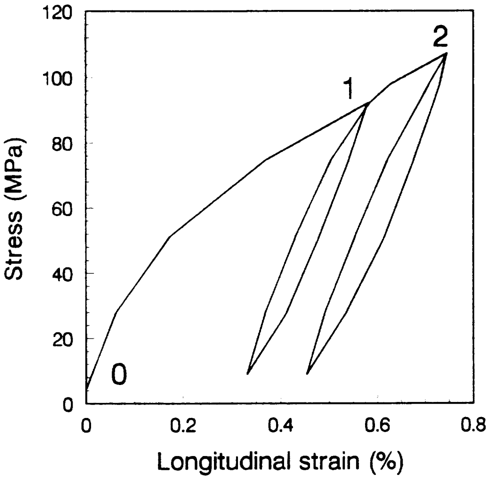

Figure 4. *Two pseudoelastic hysteretic loops of SMA2 under tensile loading after martensitic reorientation.*

previous reorientation direction as if pseudoelastic cycling load didn't happened. Unloading at Point 2, we get another pseudoelastic hysteretic loop. Experiment results show that there are also many phenomena as shown in Figure 1 of SMA at high temperature while cycling load beyond the initial unloading value.

Figure 5 shows the result of SMA1 under compression. During reloading 2 → 1, a partial cycling loading is carried out at Point 3. Unloading first 3 → 4, a new trajectory not coinciding with the curve 2 → 3 is obtained. Reverse loading from Point 4, the curve did not return along the previous unloading path. But the material can remember the initial unloading point, i.e., the curve can return to Point 3. Therefore a small pseudoelastic hysteretic loop was obtained. Crossing Point 3 and loading continuously, the curve goes forward along the initial path. The partial cycling load 3 → 4 → 3 does not affect the material's thermomechanical response. This indicates that the material has remembered the behavior of Point 3 completely. A similar result was obtained through partially cycling load at Point 5. Finally, the curve goes back to Point 1. These characteristics are similar to that showed in Figure 1(b).

If external force is unloaded to zero at different step in the reverse loading process, similar cyclic phenomena as that showed in Figure 1(a) of SMA at high temperature can be obtained. Figure 6 shows the result of SMA2 under compression measured by extensometer. There are three hysteretic loops with different sizes. The large loop contains smaller loops and parts of these three loops coincide with each other at the stage of reverse loading.

Figure 7 shows the stress-strain curve obtained by partially cycling load during unloading process. First, unloading from Point 1 to Point 2, with a partial cycling load 2 → 3 → 2 near Point 2, a small loop is obtained. Then loading again at Point 2, the curve arrive at Point 4 through Point 3. Finally, a total cycling load is carried out from Point 4 and the curve return to Point 4(6). Normally, Point 4 should coincide with Point 1 but there is a deviation be-

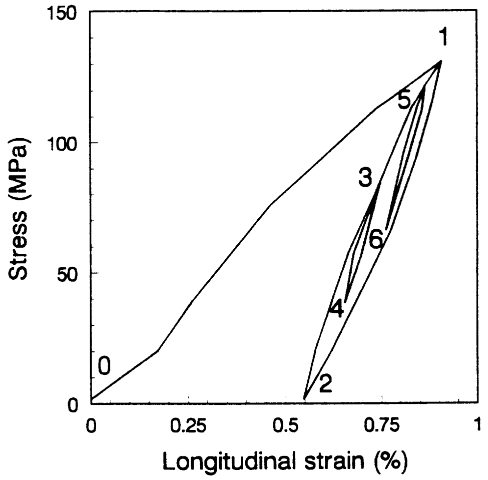

Figure 5. *Partial hysteresis loops obtained by partially cycling load during reloading process of SMA1 under compression.*

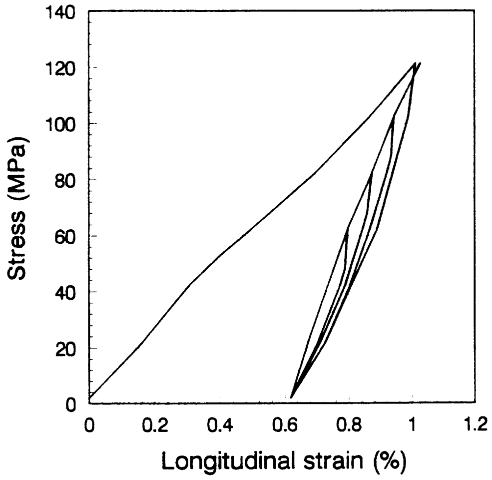

Figure 6. *Unloading at different step during reloading process in a compression test of SMA2 measured by extensometer.*

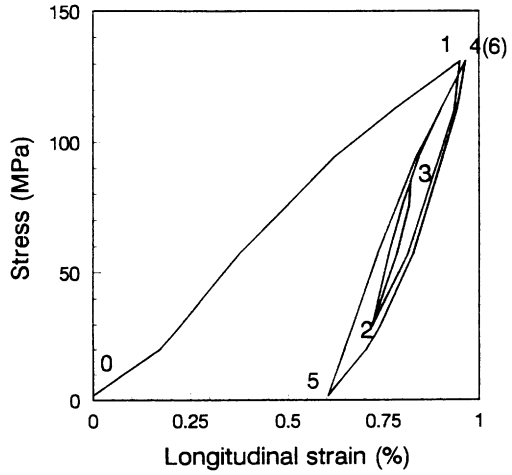

Figure 7. *Partially cycling load during unloading process in a compression test of SMA1.*

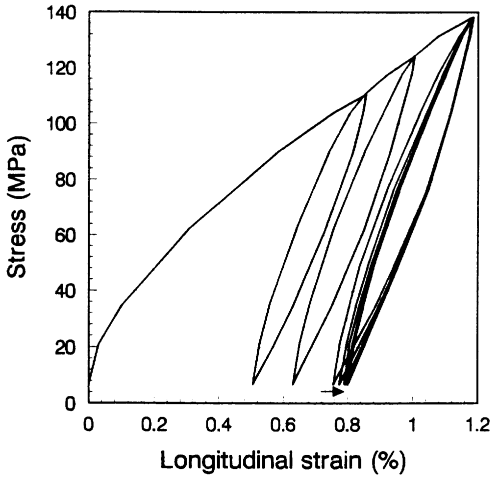

Figure 8. *The change of hysteretic loops with the number of cycling in a tensile test of SMA1.*

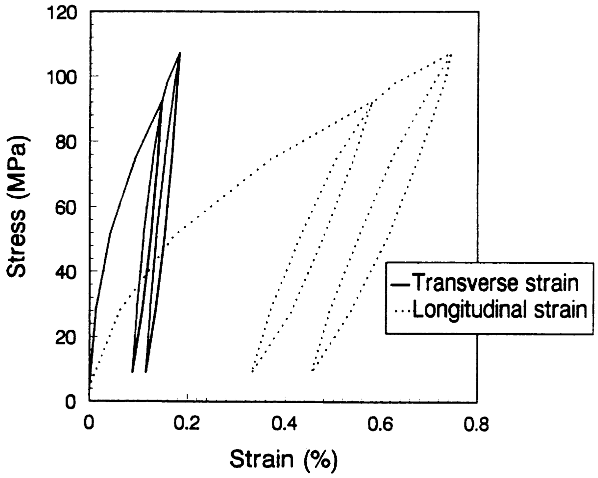

Figure 9. *Longitudinal and transverse pseudoelastic deformation of SMA2 in a tensile test measured by strain gauge.*

tween Point 1 and Point 4. As pointed out by many researchers [for instance, see Müller and Xu (1991)], this deviation also appears in the pseudoelasticity of many SMA sometimes at high temperature due to the forward and reverse martensitic transformation. Sometimes cycling loops cannot coincide completely with cycling load. But after several cycles, the loops tend to be stable. Figure 8 shows the increase in stability that after three cycling the loops almost coincide.

The longitudinal and transverse deformations of SMA2 are also measured by foil strain gauge in the same time. Figure 9 shows the tensile result. Although transverse deformation is far smaller than longitudinal deformation, its deformation behavior is similar to that of the longitudinal one. The transverse deformation shows good pseudoelastic behavior after reorientation.

DISCUSSION AND CONCLUSION

The test results of two kinds of material under different loading conditions, measured by both average and local approaches, indicate that Cu-Zn-Al polycrystalline SMA has pseudoelastic deformation behavior after stress induced martensitic reorientation at low temperature ($T_{test} < M_f$). The required condition is that applied stress does not exceed the initial unloading value. Under this condition different pseudoelastic hysteretic phenomena are obtained, which are similar to that of SMA under stress induced forward and reverse martensitic transformations at high temperature ($T_{test} > A_f$). In order to obtain stable pseudoelasticity, cycling load must be carried out several times. All these pseudoelastic hysteretic loops indicate that the microstructure of the material has changed in these pseudoelastic processes. This new pseudoelastic behavior of Cu-Zn-Al polycrystalline SMA at low temperature after stress induced martensitic reorientation awaits further theoretical study.

REFERENCES

Delaey, L., R. V. Krishnan, H. Tas and H. Warlinot. 1974. "Review: Thermoelasticity, Pseudoelasticity and the Memory Effects Associated with Martensitic Transformations", *J. Mater. Sci.*, 9:1521-1555.

Müller, I. and H. Xu. 1991. "On the Pseudo-Elastic Hysteresis", *Acta Metall. Mater.*, 39:263-271.

Ortin, J. 1992. "Preisach Modelling of Hysteresis for a Pseudoelastic Cu-Zn-Al Single Crystal", *J. Appl. Phys.*, 71:1454-1461.

Otsuka, K. and K. Shimizu. 1986. "Pseudoelasticity and Shape Memory Effects in Alloys", *Int. Metals Reviews*, 31:93-114.

Sun, Q. P. and Hwang, K. C. 1993. "Micromechanics Modelling for the Constitutive Behavior of Polycrystalline Shape Memory Alloys—I. Derivation of General Relations; II. Study of the Individual Phenomena", *J. Mech. Phys. Solids*, 41:1-17.

Sun, Q. P. and K. C. Hwang. 199. "Micromechanics Constitutive Description of Thermoelastic Martensitic Transformations", in *Advances in Applied Mechanics*, J. W. Hutchinson and T. Y. Wu, eds., New York: Academic Press, 31:249-298.