On the Hysteresis in Shape Memory Alloys

Huibin Xu and Ingo Müller
Physikalische Ingenieurwissenschaft, TU-Berlin, FRG

1. Introduction

The austenitic-martensitic phase transformation and the twinning process in shape-memory alloys are hysteretic. Hysteresis loops appear in load-deformation diagrams and in deformation-temperature diagrams.

In some applications the hysteresis is welcome and one likes it to be wide. This is the case, if one uses shape memory alloys for clamps and splints, as in the medical field, or for couplings. In other applications the hysteresis is inconvenient, because it implies a dissipation. Thus in many of the proposed heat engines working with shape memory alloys the hysteresis loop traversed in each cycle signifies a loss.

Therefore the question arises as to how to control the size of the hysteresis. For that purpose experiments were conducted with tensile specimens of two materials, viz. Cu-26Zn-6.2Al (wt%) and of Ti-51.0 at%Ni.

2. Preparation of Specimens, Experimental Procedure

Ingots of Cu-Zn-Al were hot rolled at 800°C to sheets of 1 mm thickness. The specimens of 60 x 12.5 x 1.0 mm^3 in effective size were heated at 850°C for 1 hour in argon atmosphere and quenched in hot oil at 120°C. Subsequently they cooled down in the quenching bath.

The NiTi ingots were prepared in an induction furnace under high vacuum and annealed for homogenization. The specimens were prepared in the same manner as the CuZnAl specimens except that the quenching took place in ice water. Some NiTi specimens were also aged at 420°C for 30 min. and quenched in ice water.

The specimens were enclosed in a heating chamber and subjected to heating-cooling cycles under a prescribed load. The resulting deformation was monitored. These tests were performed on an Instron testing machine which is capable of oscillating loads with frequencies up to 100 Hz.

3. Experimental Results

3.1. Effect of Mechanical Vibration

A specimen of CuZnAl loaded in tension with a constant force of 0.5 KN was heated and cooled by a cycling liquid. After several temperature cycles we obtained a regular deformation-temperature curve which is shown in Figure 1 by the outer hysteresis loop.

The specimen was then subjected to a load vibration of amplitude 0.2 KN around the mean value 0.5 KN with 30 Hz. After this "training" the deformation-temperature diagram exhibited a smaller hysteresis as shown by the inner curve in Figure 1. The width of the hysteresis had decreased from 12.6°C to 11°C, i.e. by about 12%.

Other attempts with different, even higher frequencies were not effective;

they did not lead to a further decrease of the width of the hysteresis. This research continues. We are planning to apply a wider range of frequencies than can be done with the Inston machine. In particular, we plan to excite vibrations with piezo-crystals and hope to decrease the width of the hysteresis by more than 12%.

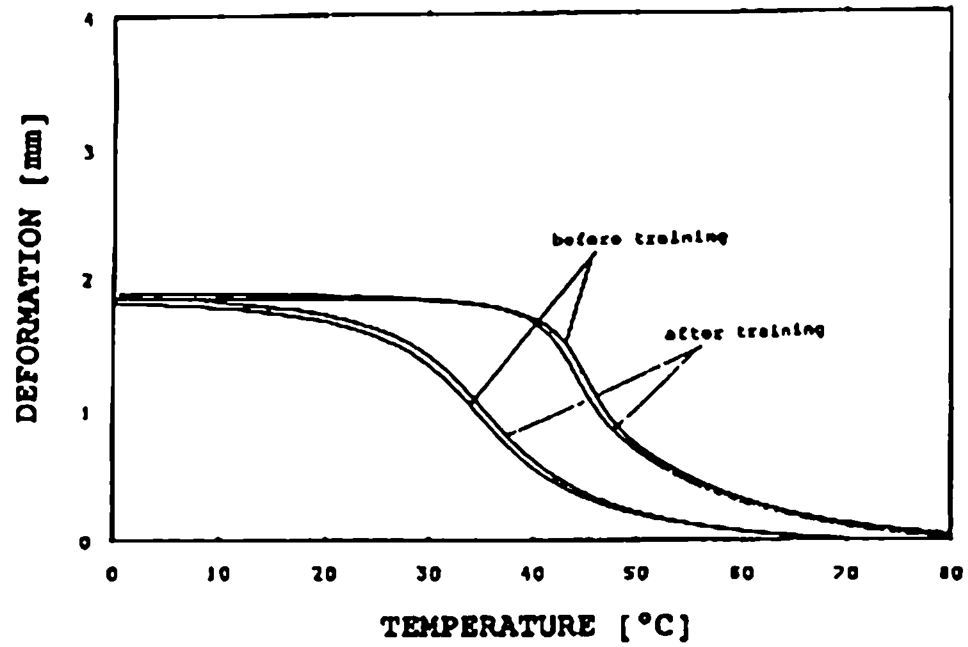

Figure 1: Effect of vibration on hysteresis.

3.2. A Reversible Transition in NiTi

A NiTi specimen prepared as described in Section 2 but without aging exhibits the deformation-temperature hysteresis at 0.5 KN shown in Figure 2. The approximate width is 40°C and the loop lies at low temperatures.

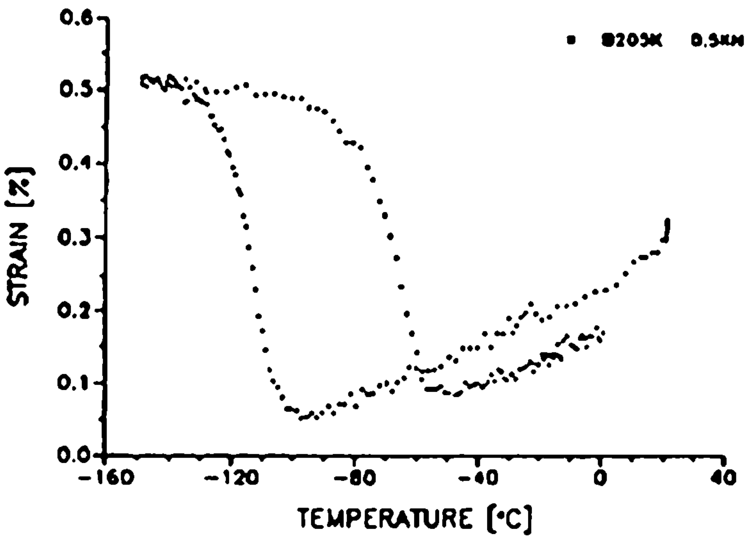

Figure 2: Hysteresis loop in Ti-51.0 at%Ni

The same specimen aged at 420°C for 30 min. and quenched in ice water shows a quite different behaviour, see Figure 3. Apparently, the transformation proceeds in two steps both in heating and cooling. because there are two steep parts in the heating and cooling curves. The high temperature step is usually associated with the formation of an R-phase. We note that this step is practically reversible, i.e. it assumes the same deformations upon heating and cooling. This fact is emphasized by the sequence of pictures on Figure 3. These figures came about by stopping the cooling process at progressively higher temperatures so that eventually only the reversible R formation is left. Thus a deformation-temperature diagram appears with approximately 0.6% strain and without any hysteresis.

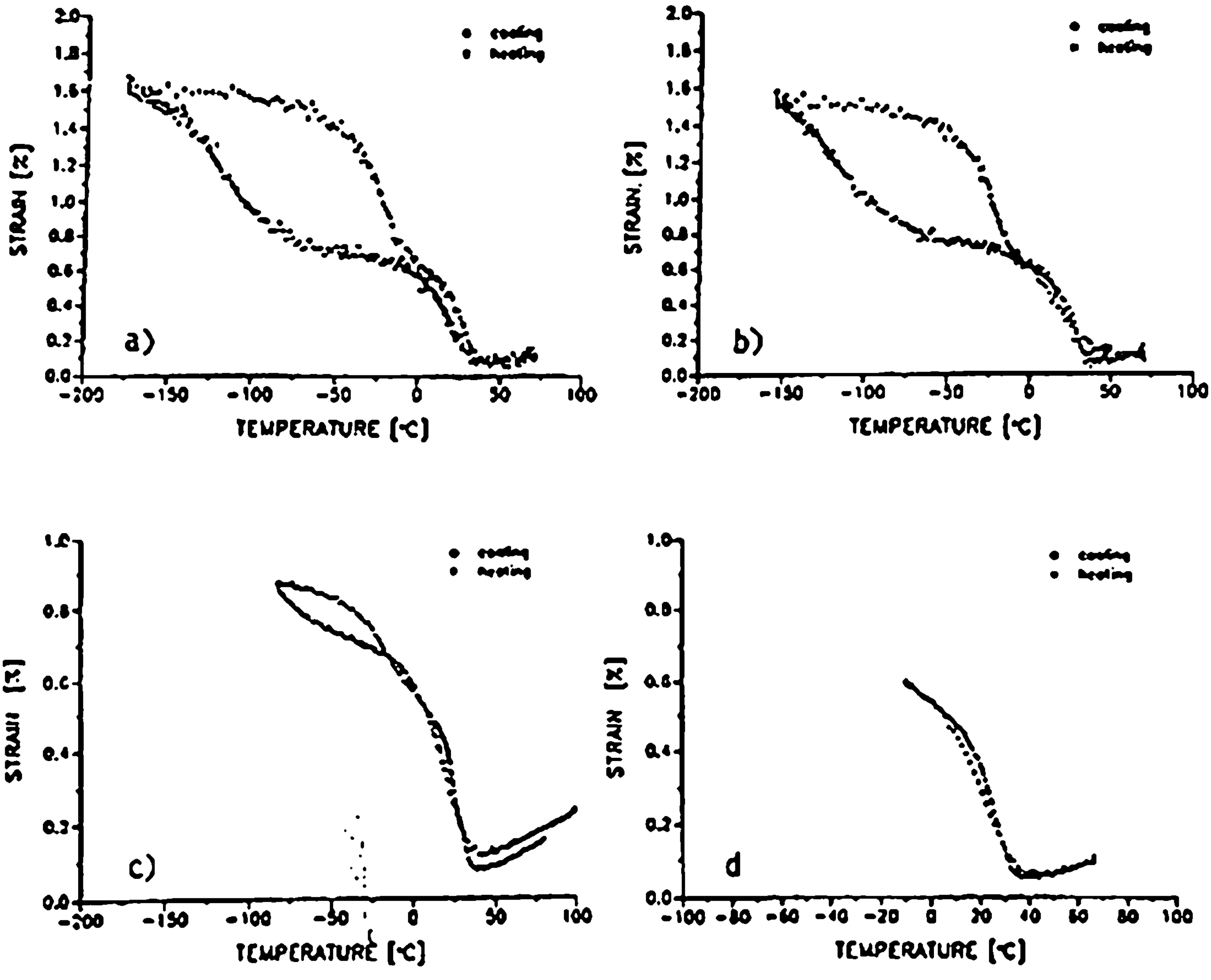

Figure 3: Deformation temperature diagrams of an aged NiTi specimen at a tensile load 0.5 KN.

The Figures 4 show the same phenomenon at a higher load. In this case the hysteresis-free, i.e. reversible strain is about 0.8%.

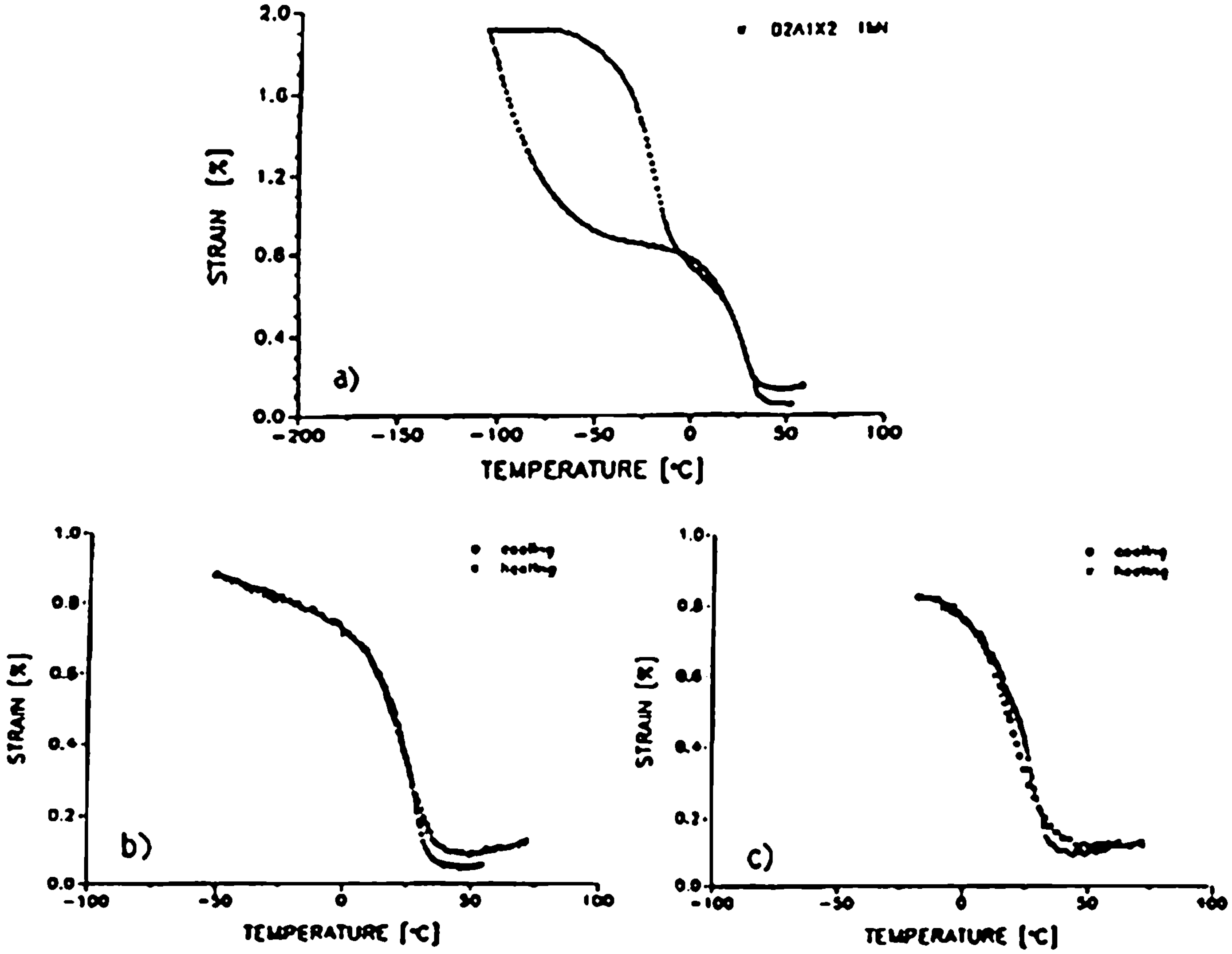

Figure 4: Deformation-temperature diagrams of an aged NiTi specimen at a tensile load of 1.0 KN.

4. Discussion

4.1. Effect of Vibration

Inspection of Figure 1 shows that the "training" of the specimen by an oscillatory force has made both transitions M -> A and A -> M easier. This must be due to an effective decrease by the oscillation of the energetic barriers that separate the positions of the austenitic and martensitic layers. The exact nature of that training phenomenon is as yet unknown.

4.2. Reversible Transition

The formation of two steps in the phase change of Figures 3 and 4 is often interpreted as due to the formation of a "premartensitic" so-called R-phase (1). The structure of the R-phase may exhibit but little distortion from the austenitic phase which has B2 structure of which CsCl is the prototype.

The Figures 5 and 6 show the lattice structures relevant here. Figures 5a and 5b present some lattice cells of the austenite. The solid lines in Figure 5b identify a tetragonal unit cell having b = c = 4.27 Å and a = 3.02 Å. In Figure 6 we have shown the monoclinic cell that emerges from the tetragonal cell of Figure 5b in an A -> M transition. This monoclinic cell has been sheared in the direction $\langle 110 \rangle_A$ with a shear system of $\{100\}_A$ and $\langle 110 \rangle_A$. The martensitic cell has nearly the same volume as the austenitic one.

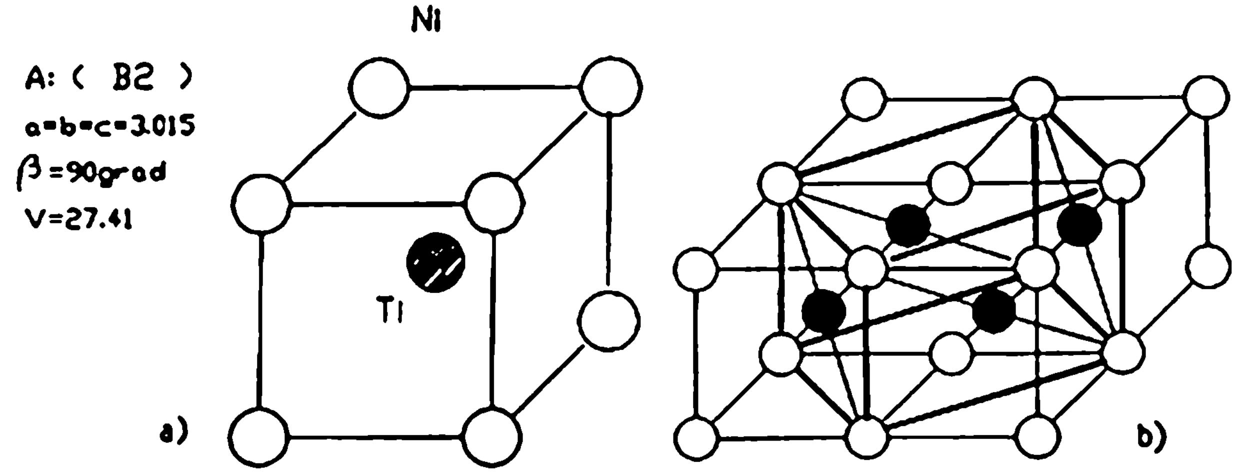

Figure 5: a) Austenite unit cell with B2 structure
b) Four B2 unit cells and one tetragonal unit cell.

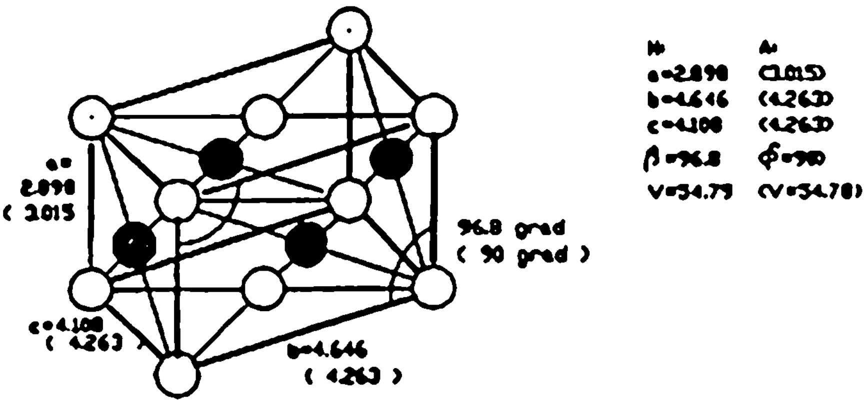

Figure 6: Unit cell of martensitic phase.

The R-phase lattice is very close to the A lattice as can be seen from an inspection of Table 1 which has been taken from the literature.

A (B2)		Ti_3Ni_4		R		M	
(hkl)	d(Å)	(hkl)	d(Å)	(hkl)	d(Å)	(hkl)	d(Å)
100	3.02	210	2.98	11.1	3.02	100	2.89
110	2.13	321	2.13	03.0	2.12	020	2.06
111	1.74	111	1.69	00.3	1.76	101	1.91

Table 1: Comparison of d-spacings of four phases [2].

The closeness reveals itself, if we look at the d-spacings which are nearly identical for the planes $(100)_A$, $(11.1)_R$ and $(110)_A$, $(03.0)_R$, and $(111)_A$, $(00.3)_R$. This fact confirms the view that the lattice cell of the R-phase is rhomboedrically distorted by a very small amount from the A-phase (see Figure 7).

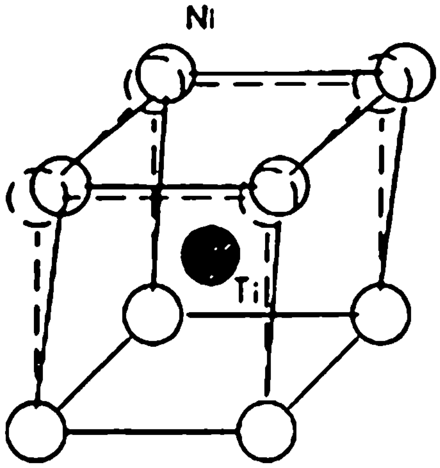

Figure 7: R phase unit cell sheared from A.

The appearance of the R-phase may be due to precipitates of Ti_3Ni_4 generated in the aging process. These precipitates are rich in Ni and that leaves the matrix poor in Ni. In that case it is known that an additional step is introduced into the transition B_2 <—> monoclinic, so that they become transitions B_2 <—> rhomboedral <—> monoclinic. Kainuma et al. [3] have observed the microstructure of the rhomboedral R-phase containing Ti_3Ni_4 precipitates. From their results it may be inferred that the strain field caused by the precipitates causes the R phase, because there is a very small difference of the d-spacings between the R-phase and the Ti_3Ni_4 precipitates, see Table 1.

4.3. Size of Hystereses

We have seen that the transition A <—> R is not hysteretic, while the transition R <—> M has a strong hysteresis. On the other hand, from Table 1 we have concluded that the A <—> R transition produces but a tiny deformation of the lattice, while the R <—> M transition involves a big shift of the lattice. These two observations may well be connected. Indeed, according to Müller [4], the size of the hysteresis is determined by the interfacial energies of the phase boundaries and these will be big, if the lattice distortion is big. On that count we do not expect a hysteresis in the A <—> R transition.

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