



THE INFLUENCE OF DISLOCATIONS ON THE MARTENSITIC TRANSFORMATIONS
IN SHAPE MEMORY Cu-Zn-Al ALLOYS

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Abstract

During the martensitic transformation the properties of the dislocations change. Their Burgers vector and their strain field are different in both phases. This leads to several interesting effects. The presence of dislocations in the L₂ ordered high temperature phase changes the relative phase stability and affects the transformation temperature. It also leads to thermoelasticity in single interface transformations. During the transformation dislocations are produced in the martensitic phase. After repeated cycling through the transformation temperature dislocations accumulate and lead finally to fatigue fracture. The presence of dislocations can favor certain variants and lead to the two way shape memory effect.

Introduction

Dislocations influence the martensitic transformation in shape memory alloys in several ways:

- a) It is well known that a previous plastic deformation increases the transformation hysteresis. This has also been observed when β -phase single crystals are deformed on a single slip system (1).
- b) Since the martensitic transformation is associated with a change in distance between atoms, and with differences in the elastic constants, the elastic energy of the dislocation is modified in different ways depending on the orientation of the dislocation, considering line directions and Burgers vectors, with respect to the martensite variants. In addition, the Burgers vectors of some dislocations may lose their translation symmetry giving rise to the formation of stacking faults (2,3,4). These changes in the dislocation energies modify the relative stability between the phases and the variants, producing a shift in the M_s temperature (1,5) or eventually making the appearance of some variants more favourable than others (2,3). This latter fact together with the arrangement of the dislocations in bands parallel to the habit plane was suggested to be one possible reason for the two way memory effect (2,3).
- c) Dislocations can be produced not only by plastic deformation in the high temperature phase before transformation, or in the martensite, but also during the martensitic transformation either temperature (6,7,8) or stress induced (9,10,11), leading to a modification of the subsequent transformation cycles.

These interactions lead to several interesting effects, three of which will be discussed in the following, due to their importance for the technological applications, namely the thermoelasticity in single variant transformations, the fatigue due to thermal or stress cycling

through the transformation range, and the two way shape memory effect.

Intrinsic thermoelasticity in single interface transformations.

Consider a β -phase single crystal which has transformed partially to a thin single variant martensite, one of the interfaces being at $x = 0$, figure 1a.

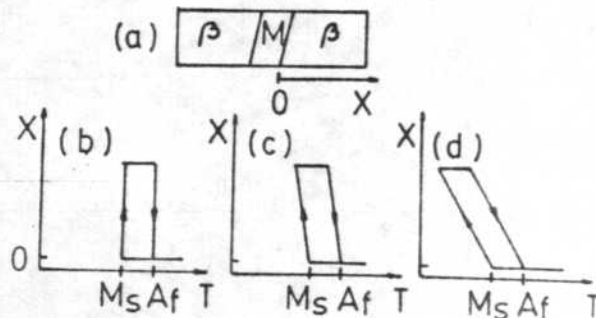


Fig.1: single interface transformation of a martensite plate M into the β phase matrix (a). Interface position x as a function of temperature T for the ideal case (b), for intrinsic thermoelasticity after cooling in air (c) and quenching into water (d).

When the sample is cooled homogeneously, it can be expected that at the M_s temperature the interface starts to move, leading to the transformation of the β phase crystal, as shown in figure 1b in the plot of interface position x versus temperature; on reheating the retransformation to the β phase starts and goes to completion at A_s .

What one observes is different, however, (4): On cooling, a continuous undercooling is necessary to keep the interface moving (fig. 1c,d) whose degree depends on the previous heat treatment: After air cooling the specimen from high temperatures, the inclination of the hysteresis cycle is smaller (fig.1c) than after quenching into iced water (fig.1d).

The reason for this unexpected behaviour is related to the fact that for those dislocations of the high temperature β phase, whose Burgers vector does not lie in the basal plane of the martensite after transformation, the Burgers vector no longer is a translation vector in the 18R martensite. Therefore, when a moving interface intersects a dislocation, it trails behind a fault which originates at that dislocation. With increasing displacement of the interface, more and more dislocations are cut, and the density of faults increases leading to a decrease in relative stability of the martensite with respect to the β phase, and consequently to a decrease of the M_s temperature with increasing path. When by quenching more dislocations are produced (4,8), the required decrease in M_s to keep the interface moving is higher (figure 1d), than when on slow cooling a smaller density is induced. During the retransformation the faults disappear together with the martensite. Thus, the fault energy is recovered and parallel branches in the hysteresis loop are obtained.

This influence of dislocations not lying in the basal plane of the martensite on the martensitic transformation should have several effects on the microstructure of the martensite.

- a) A higher dislocation density should lead to thinner martensite plates after cooling without applied stress: After a critical undercooling it becomes more favourable to nucleate new plates than to expand existing ones. This produces a finer and more complex distribution of martensite variants (8).
- b) In stress induced transformations a unique variant of martensite is obtained. However, in general due to the intrinsic thermoelasticity, instead of a single interphase transformation, several parallel plates are formed which then collapse. Since these plates differ in their stacking sequence, planar defects parallel to the habit plane are left (12,13). These defects, among other, serve as obstacles to the movement of dislocations in the martensitic phase (14).

It may be thought that by deliberately creating dislocations during tensile plastic deformation in the β phase, a large number of stacking faults is produced during the subsequent transformation induced by tensile stresses. This, however, is not the case as can be seen with reference to the stereographic projection of figure 2.

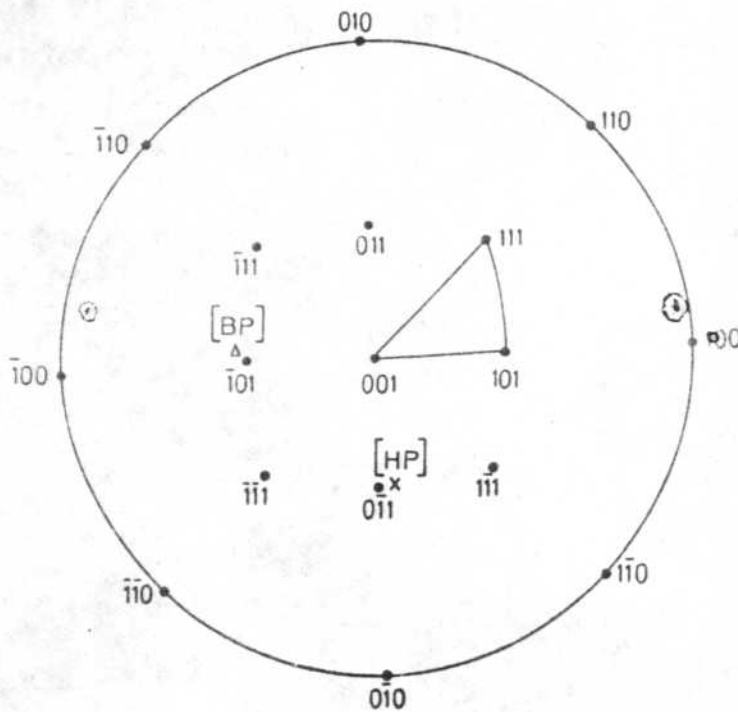


Fig.2: Stereographic projection of the high temperature β phase. For tensile axes in the unit triangle the most favorable martensite variant has the habit plane at [HP], and the basal plane at [BP]. Dislocations induced in the β phase have the Burgers vector parallel to $[1\bar{1}1]$.

A plastic deformation of the β phase creates screw dislocations with \vec{b} parallel $[1\bar{1}1]_{\beta}$ (15). If the martensitic transformation is subsequently induced by tension along the same axis, the Burgers vector of the dislocations lies in the basal plane of the induced variant and has symmetry translation properties of the basic 18R structure. Thus the interaction of the transformation with the dislocation is not due to the creation of stacking faults, as in the case of the intrinsic thermoelasticity. The presence of the dislocations manifests itself mainly in a shift of the critical resolved shear stress for the transformation to higher values (5), due to changes of the elastic energy.

Fatigue associated with the stress cycling through the martensitic transformation



When a single crystal of the β phase is stressed in tension or compression a single variant martensite crystal is induced, as explained above. It retransforms back upon unloading with a complete shape recovery. It can be expected therefore, that the original single crystal is restored, and that it is not modified on repeated cycling. The observations, however, are at variance with these expectations:

- On repeated cycling in tension or compression at room temperature or at liquid air, a continuous increase in dislocation density is observed in the interior of the bulk (10,11,16,17). See Fig. 3.

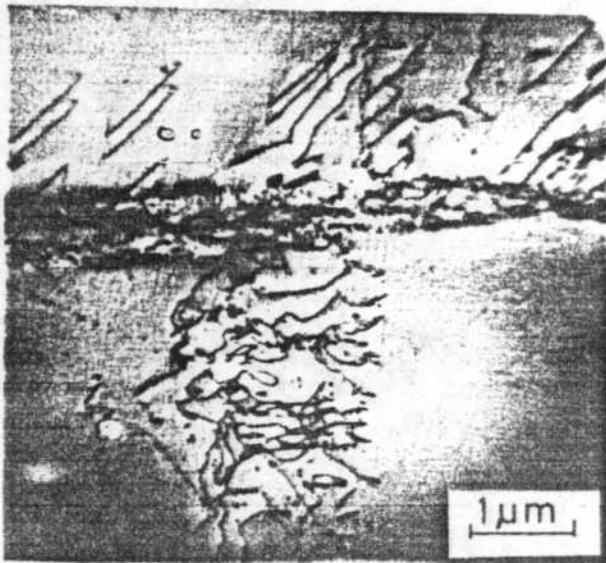


Fig.3: Dislocations arranged in bands[ⓐ] parallel to the habit plane (horizontal) and to the basal plane (vertical) after pseudoelastic fatigue cycling. Foil surface nearly (001) β (16).

- On the sample surface intrusions and extrusions are formed, which lead to surface cracks and finally fatigue cracking at room temperature (10,11,16), see Fig. 4. It should be noted that the extrusions and intrusions are not only present in single crystals, but that they have also been observed in polycrystals (18).

At liquid air no extrusions[ⓑ] are observed, instead cracks are formed which are not associated with surface upheavals but look more like brittle cracks (17).

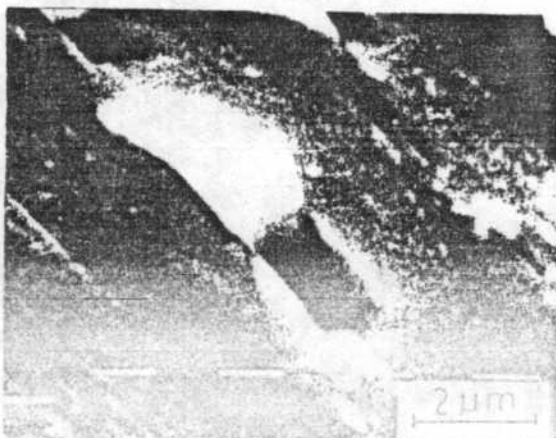


Fig. 4: Single intrusion-extrusion defect (left), formation of cracks by coalescence of defects (right). Scanning electron microscopy (10).

Thus, fatigue is also found associated with the martensitic transformation although the shape change during the transformation is

not due to dislocation movement as in the more commonly observed fatigue during plastic deformation. The dislocations that are formed during the cycling and are retained in the β phase have been analysed by transmission electron microscopy combined with computer simulation (11). It has been found that they are mostly of a mixed type, their line lying parallel to $[111]_{\beta}$ and $[\bar{1}\bar{1}1]_{\beta}$ in the β phase, on the $(\bar{1}01)_{\beta}$ plane which becomes the basal plane of the martensite, with the Burgers vector parallel to $[010]_{\beta}$, which corresponds to the shortest translation vector in the martensite with an inherited B2 order, and double that vector if $L2_1$ order is inherited (see figure 2). These dislocations are different from those which are formed during plastic deformation of the β phase, see above. Therefore the dislocations created during fatigue cycling cannot be due to the plastic deformation of the β phase matrix induced by stresses from the growing martensite plates.

A recent analysis of the deformation behaviour of 18R martensitic single crystals (14,19) has shown that the deformation system is $(0018)[010]$ (in orthorhombic indices) and the critical stress is about 77 MPa. These dislocations are the same as those created during fatigue suggesting that the latter are indeed formed in the martensite phase. However, for the fatigue experiments performed in tension the Schmid factor for the plastic deformation of the martensite is very low (11). Such a critical stress was not reached in most of the fatigue tests. As an alternative, two possible sources for the creation of internal stresses should be taken into consideration: On one hand the dislocations, which are grown in or are produced during preceding cycles may act as obstacles for the propagation of martensite plates and thus create high local stresses (10). On the other hand, a relative volume change of $8 \cdot 10^{-4}$ is associated with the martensitic transformation (20). Although being small, it can lead to sufficiently high stresses in front of a thick martensite plate in order to create additional displacements on the close packed planes of the martensite tip (21). This mechanism could account for the fact that the dislocation tangles which are observed lie preferentially at the intersection of the habit plane and the close packed basal plane of the martensite.

The extrusions and intrusions on the crystal surface are principally seen in that region, for which the direction of the martensite shear lies in the surface. It had been suggested therefore that a martensite plate which is held up by dislocation tangles near the surface creates around it high strain fields which are relaxed by deformation normal to the surface (10). This deformation cannot be due to slip in the martensite, since its Burgers vector has its main component in the habit plane parallel to the martensite shear direction, whereas the extrusions would require a large component normal to the martensite shear direction. Moreover the critical shear stress for plastic deformation has been found to be largely temperature independent between room temperature and liquid air (22), therefore the change in fatigue crack formation between room temperature and liquid air cannot be understood either by this deformation mechanism. Similar arguments can be presented to show that it is unlikely that deformation of the β phase matrix produces the extrusions: The slip vector in the β phase is $[111]_{\beta}$, its projection on the habit plane makes an angle of approximately 35° with that surface orientation at which the extrusions are most pronounced, a difference that should not exist and that is difficult to account for. In addition the critical stress for plastic deformation of the β -phase does not depend strongly on temperature, at

least in Cu-Zn single crystals for which data exist (23).

Thus, we conclude that the deformation mechanism which is responsible for the formation of extrusions and intrusions is either an unknown slip mechanism, whose critical stress increases strongly with decreasing temperature, for which till now there is no experimental support, or a mechanism which involves the stress induced movement of vacancies.

A major involvement of vacancies in the formation of the extrusions, although speculative at this moment, could account for the change of fatigue crack formation at liquid air, where vacancies are immobile, and also for the formation of extrusions normal to the surface and in a region where the martensite shear, when held up by obstacles, creates the largest strain field. That during the fatigue cycles vacancies are created would not be surprising, in addition it is found that the transformation stress strain curve changes considerably if the cycling is interrupted and recovery is permitted to occur (10).

The two way shape memory effect (TWSME)

When a β phase crystal is cooled through the transformation temperature, its shape is changed by the application of forces, but on retransformation to the β phase it regains its original shape. This effect is due to the growth or shrinkage of martensite variants by the movement of the interfaces until the shape has adjusted to the applied forces. On a second cooling without applied stresses the shape of the samples remains unaltered, unless a special training treatment is applied which leads to a preferential growth of certain martensite variants. This can consist of a cycling in temperature under a given shape change which is kept constant during the temperature variations (24).

It is clear that the two way shape memory effect is due to the formation of dislocations, which are retained in the β phase, and which act as sites for preferential martensite variants. When the cycling is done with a β phase single crystal, by changing the temperature at a given small applied stress, or by cycling the stress within a small range at a given temperature, a TWSME is not observed (25), unless the number of cycles is large (26), although by transmission electron microscopy a great number of retained dislocations are observed (25,26). It has been reported that, if the martensite is tensioned and plastic irreversible deformation is induced, the TWSME is strongly enhanced (26).

The presence of dislocations can influence the selection of variants in several ways:

- they facilitate the nucleation of specific variants with respect to others.
- they change the free energy of transformation due to the presence of single dislocations.
- they create internal stresses by groups of dislocations with a preferential Burgers vector.
- they suppress the growth of those variants which are associated with the creation of stacking faults.

As mentioned in the introduction, the length of the Burgers vector changes on transformation, this together with changes in the elastic constants in both phases leads to a modification of the free energy of isolated dislocations. This contribution has been evaluated

quantitatively (2,3). (It should be noted that the energy of dislocations in ref. (3) are indeed given in nano-joules/meter instead of milli-joules/meter as it is written). During stress cycling at constant temperature dislocations are induced with positive and negative Burgers vectors in nearly equal amounts (11,26). By plastic deformation of the martensite dislocations groups of preferentially one sign are introduced, and internal stresses are created. It seems (26) that they enhance considerably the TWSME. It is not clear whether a net internal stress around the dislocation bands is indeed required for the TWSME, since already the presence of dislocation bands parallel to the habit plane of the induced variant with opposite Burgers vectors in equal amounts can favor the spontaneous growth of this variant in the following way: The energy of the dislocations is higher in the β phase than in those variants of martensite whose basal plane contains the Burgers vector (2) (3). Under these conditions the maximum gain in energy will be obtained for that martensite variant whose habit plane grows parallel to the dislocation bands (2). It should be remarked that stress experiments in tension are not well suited for a quantitative evaluation, since instead of plastic deformation in 18R a transformation to the fct 6R structure is generally induced (27). Moreover the Schmid factor for plastic deformation in tension is small (26). It has been shown that by compression tests the plastic deformation of 18R martensite can be induced without other competing reactions (19). Therefore the TWSME should be studied in compression samples. These experiments should also decide what role is played by the modifications of the nucleation process.

This discussion makes clear that the training for the TWSME is a complex process, especially in the industrially used polycrystalline materials, and that a better understanding of the underlying processes can be obtained only by carefully designed experiments, which till now are lacking.

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