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SHAPE MEMORY IN Ti-10V-2Fe-3Al

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Introduction

A stress assisted martensitic transformation from the BCC β structure to the orthorhombic α" phase has previously been reported in the commercial β-Ti alloy, Ti-10V-2Fe-3Al (1). The transformation is "assisted", or "induced" by relatively low stress levels (on the order of 250 MPa), and can accommodate as much as 5-6 % strain before the true, or dislocation, yield point is reached. Such a behavior is clearly a prerequisite for shape memory, but by itself is not sufficient. Other requirements, which Ti-10V-2Fe-3Al also satisfies, are that the specific volume of the parent and martensite phases be nearly identical, and that the martensitic transformation be thermoelastic, and not "burst", in nature.

Another proposed requirement for shape memory is that the parent phase, and thus the martensite, must be ordered (2,3). Common shape memory alloys such as NiTi and the β-brasses clearly fulfill this last requirement. An apparent exception to this rule is an Ti-35Nb alloy, which though not ordered, has been reported to exhibit a significant shape memory behavior (4). The purpose of this paper, is to present some observations of shape memory in Ti-10V-2Fe-3Al. The emphasis here will be placed on describing the physical manifestations of the effect. A more detailed study is underway to understand the α" → β reversion transformation, and will be reported upon in a later publication (5).

Experimental

The material used in this study was taken from a commercially produced ingot from RMI. The composition of the ingot was reported as:

Element	V	Al	Fe	N	C	O	Ti
Wt. Percent	9.3	3.2	1.8	0.01	0.03	0.082	bal.

The β-transus temperature of this heat was metallographically determined as 800°C. All material used in this study was in the β-solution treated and quenched condition. Solution treatment was done in argon at 850°C for 30 minutes, and quenching was done into agitated water. Investigation of the as-quenched structure revealed a large, equiaxed β-grain structure, with very fine athermal ω particles or modulations.

Dimensional changes during deformation and shape memory treatments were determined by monitoring the migration of scribe marks with the aid of a measuring microscope. Dilatometry results were obtained in a Netzch dilatometer modified to improve low temperature accuracy. The back-stress tensile experiments were done in a servo-hydraulic Instron machine operating in the load controlled mode; strains were then measured by monitoring the actuator position as the actuator moved to maintain the set load. Torsion tests were conducted in a "homemade" rig, using an angular transducer to measure strain. In both the back-stress and the torsion work, specimens were heated using two hot air guns capable of heating the specimens to 300°C within 3 minutes. Specimen temperatures were recorded through a thermocouple welded to the specimen surfaces.

Results and Discussion

Gauge lengths from tensile specimens were removed after deformations of 0-6 %, and placed in a dilatometer. Upon heating, the specimens were found to contract, restoring their original geometry (Figure 1). The temperatures at which shape recovery begins and ends are customarily called the A_s and the A_F temperatures; they are, in this case, 166°C and 240°C respectively. Figure 1 also shows that no reverse shape change, or return to the deformed geometry, was noted during subsequent cooling; the memory movement is entirely an irreversible one-way effect. This should be expected since the M_s temperature in this particular alloy is believed to be below -170°C (1,5). The unusually large A_s, A_F, M_s, M_F hysterises of this alloy is thought to be due to a competition between the formation of α'' and the extant athermal ω phase formed during quenching (5).

By changing the dilatometer heating rate, it was found that the most complete shape recoveries were obtained by the fastest heating rates (Figure 2). The fastest heating rate measured during these tests was established by immerson in molten salt, and recording only the lengths before and after immersion. Using this method of heating, the magnitude of the intial strain was changed, to obtain an indication how efficient the memory effect was as a function of strain. The results (Figure 3) show that perfect recovery of strains less than 3 % was possible, and that recovery of strains beyond 5 % was extremely limited.

Experiments also were done to measure the shape recovery with an external load resisting the recovery, and thus, determine the work that the movement could produce. Specimens deformed in tension were heated with various fixed tensile stresses applied, as described above, and exemplified in Figure 4. Loads less than 100 MPa were found to have no measurable influence on the recovery process, while loads above 250 MPa were found to essentially prevent shape recovery. The maximum work measured (as determined by stress times recovered strain) was 0.43 Joule per gram, which is about one half of that measured in NiTi (6). This value corresponded to 60 % recovery of a strain of 2.8 %, against an applied load of 142 MPa. Two other differences were noted between "free" and "constrained" recovery. First, A_F was found to increase subtantially, while A_s often decreased. Secondly, a small reversible, two-way effect (about 0.5 %) was observed with back stresses of about 150 MPa. Apparently at this point the applied load was able to influence the orientations of martensite which were forming during cooling; or, in other words, the martensite was being "assisted" during cooling by the applied stress, thereby reproducing the original tensile strain.

The memory recovery was also measured in torsion. A typical torsional temperature-strain curve is shown in Figure 5. The most notable difference between this curve and the tension curves such as is shown in Figure 1 is that a two-way effect, or reversible memory movement was observed in torsion, without an externally applied stress. The same tests were conducted using hollow torsion specimens to reduce the strain inhomogeniety, and the two-way movement was eliminated. Thus the two-way effect seen in torsion seems to be just a manifestation of the two-way effect seen in the back-stress experiments. From Figure 2, one can see that the completion of recovery is dependent on strain, or in the case of the torsion specimen, on the radial distance from the specimen center. Material near the center of a solid specimen will try to return 100 % of the original deformation angle, while material near the outer diameter will have a certain amount of permanent deformation, and thus resist returning to the original geometry; the net effect is that the outside of the specimen acts as an external load working against the inside. Clearly when one uses a hollow specimen, with better defined strains, the recovery is more homogenious, and no two-way effect is observed. Specimens deformed in bending gave results quite similar to those deformed in torsion.

It has been conventionally believed that ordering is a requirement for shape memory (2,3). The wisdom for this belief is sound; there are 24 variants of the $\alpha'' \rightarrow \beta$ transformation (4), only one of which restores the original shape. An ordered matrix means that one of these β variants is prefered since only the original variant restores a perfectly ordered parent phase. Thus ordering provides the mechanism of memory.

In Ti-10V-2Fe-3Al, as well as in Ti-35 Nb, the parent phase is not chemically ordered, and thus the "memory" of the original β variant is dependent on other means, such as the dislocation networks and residual stress fields surrounding the martensite plates. One should be reminded, however, that the athermal ω modulations found in the β solution treated condition bear some resemblance to ordering; in a sense, they are a structural ordering (7). It is certainly not clear that the ω modulations should have any effect on the $\alpha'' \rightarrow \beta$ transformation, but it is nevertheless interesting to note that both Ti-35Nb and Ti-10-2-3 athermally decompose to ω on quenching. Whatever the chief mechanism is, be it dislocations, residual stresses, or ω ordering, it is clear that reasonably large memory effects can be produced without chemical ordering.

Conclusions

A one-way shape memory with an unusually large temperature hysteresis has been reported in the disordered β-Ti alloy, Ti-10V-2Fe-3Al. The effect produces 100 % recovery of strains up to 3. %, and is operable between 166°C and 240°C. Although the effect was found to be completely irreversible in tension, a small reversible component was detected in deformation modes having an inhomogeneous character, such as torsion and bending.

The high transformation temperatures and irreversible nature of the transformation make the alloy a potentially interesting candidate for certain joining applications since it would not be necessary to deform and store couplings in liquid nitrogen. On the other hand, the stresses generated by the effect are currently small compared to NiTi and the β-brass alloys, so it may not be possible to generate the forces required for sound coupling. The two-way effect has some potential usefulness, but suffers from instability problems; the α'' phase is apparently stabilized by relatively short exposures to temperatures in the 200°C range, and thus the memory effect is destroyed. With additional work, these problems could possibly be solved, or at least mollified.

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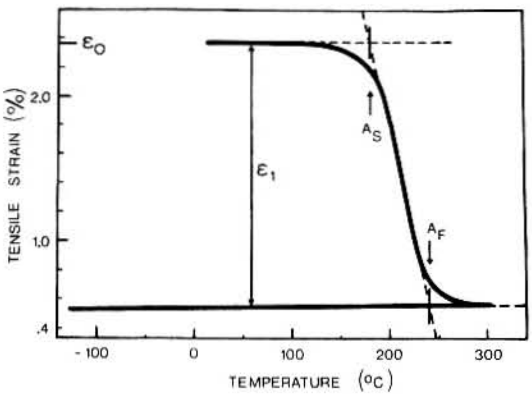

FIG. 1
Temperature-strain trace of the shape recovery process in Ti-10-2-3 deformed originally 2.2 %. The dilatometer heating rate was 8°C per minute.

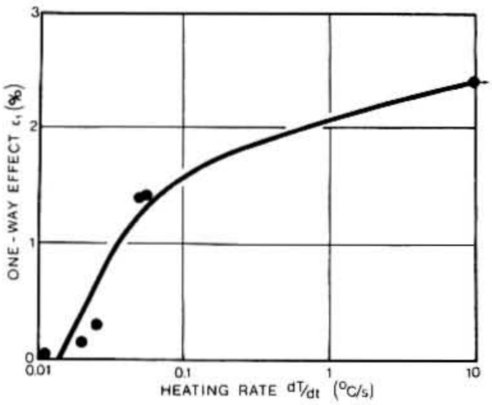

FIG. 2
The dependence of recovered strain on heating rate, after an original 2.4 % deformation. The highest heating rate was obtained by salt bath heating (> 10°C/s), the other data points are from a dilatometer.

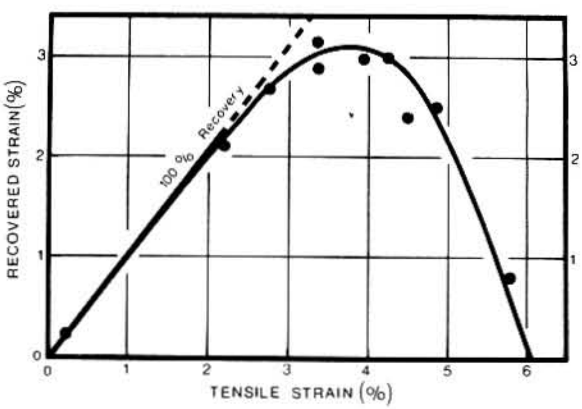

FIG. 3
Recovered strain as a function of initial strain, with heating rate maximized (salt bath heating). The dashed line represents perfect, or 100 % recovery.

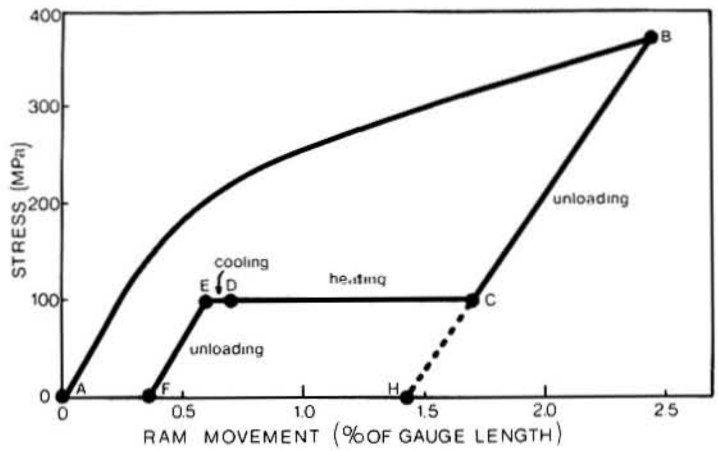

FIG. 4
Shape recovery against an applied load. Segment A-B represents the initial deformation; segment B-C unloading to the desired set point load; segment C-D the strain recovered against the set load; segment D-E the natural thermal contraction during cooling to room temperature; and segment E-F the final unloading. The parallelogram F-E-C-H represents the total work done during recovery.

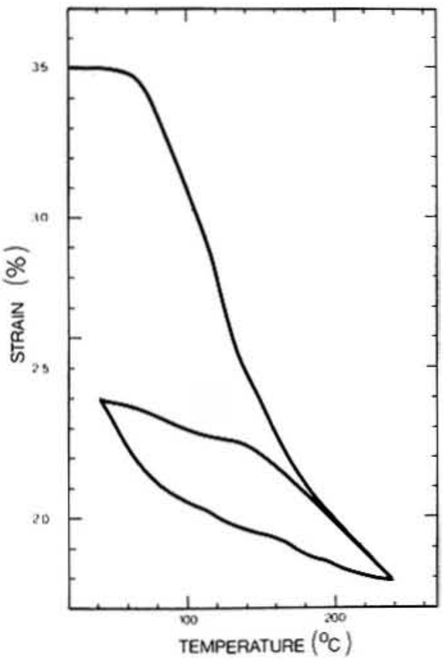

FIG. 5
Strain shown as a function of temperature after an initial tensile deformation of e = 3.4 %. Initial heating produces a 50 % recovery of the original 3.5 % strain, subsequent cooling and heating produces a closed "two-way" hysteresis loop.