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Proft, Melton, Duerig

MRS
Vol. 9
pp. 581-597

1989

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DESIGNING WITH THE SHAPE MEMORY EFFECT

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ABSTRACT

Some of the engineering aspects of shape memory product design are reviewed, with the emphasis on product screening. After a short general description of the memory effect, applications are categorized according to the function of the memory alloys: to cause motion, to generate a stress, to do work, or to store elastic energy. Each of these functions is overviewed, with schematic and practical examples, typical design problems, examples of relevant design data, alloy selection criteria, and a guideline for screening new applications.

INTRODUCTION

Substantial research has been done to understand the mechanism and crystallography of the shape memory effect. Although these issues are now largely understood, a complete mechanical characterization and a sound ability to efficiently engineer products using the effect are still lacking. The fact that product engineering has been difficult is quite understandable. Many of the usual mechanical properties such as yield strength and modulus are very strongly temperature dependent and have entirely different meanings in shape memory alloys. An entirely new set of descriptors must be invoked, with terms such as "stress rate" and "amnesia". Moreover, most of these are not state functions, but are path dependent.The field is further complicated by the fact that most designs are generally not evolutionary, but revolutionary in nature. One of the most impressive aspects of shape memory is that it can be applied in many widely different ways to a broad range of products. But this in itself has slowed progress by causing the industry to defocus, and to embark on many projects with little commercial validity.

The purpose of this paper is to overview the engineering aspects of shape memory, but with an emphasis on product screening: differentiating between what can, and what should be done using shape memory. The approach that will be followed will be to organize the various applications of shape memory into four general categories: free recovery (causing motion), constrained recovery (causing stress), actuators (doing work) and pseudoelasticity (storing elastic energy). After a short introduction to the effect itself, each will be discussed separately, with a schematic example, examples of successful applications, typical engineering properties that would be needed by a designer, alloy selection, and finally a list of key screening criteria.

THE SHAPE MEMORY PHENOMENON

The mechanism and general characteristics of shape memory have been extensively reviewed [1-15], and will be summarized here only in the briefest possible form. Shape memory describes the ability of certain metal alloys to be deformed at a low temperature and then to return to their original shape upon heating. The effect requires that a martensitic phase change occur, and the specific volumes of the martensite (the low temperature phase) and austenite (the high temperature phase) are effectively equal. When in the martensitic condition, deformation strains can be "stored" through a mechanical twinning process. The austenite phase cannot accommodate these twins, so when the material is heated and reverted to austenite, the deformation must be returned.

The above process is represented in two dimensions in Figure 1. The high temperature austenite is shown in (A). Upon cooling, martensite forms with the overall shape being preserved by creating self-accommodating twins (as shown by the alternating layers in (B). The twin boundaries are of a very low energy and highly mobile; their function is only to geometrically allow, or accommodate, the transformation. When a stress is applied, the twin boundaries are easily moved to new positions; this is illustrated in (C) after applying a shear moment and com-

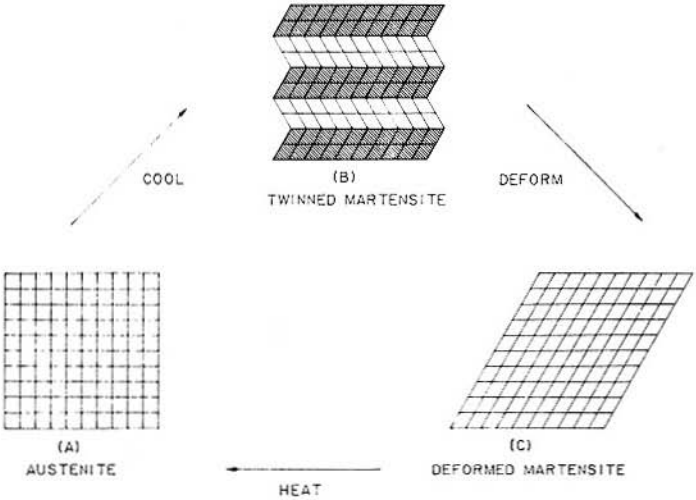


Figure 1: Two-dimensional representation of the shape memory event: the cubic austenite (A) is cooled to form twinned martensite (B), which can be unfolded or detwinned by the application of a stress. Subsequent heating reverts to austenite (C), removing all twin boundaries and returning the original, undeformed shape.

pletely de-twinning the structure. The new shape shown in (C) was arrived at without adding permanent defects (dislocations, etc) to the material. Upon heating, the original austenite structure (A) is again stable. The austenite phase cannot crystallographically accommodate these twins, so that the original shape must be returned no matter what the twin state of the martensite. Thus any deformation of the martensite, provided it is small enough to be accommodated by twin movement, is reversible upon heating. The situation is the same in three dimensions, except that either three or four twin variants (depending on the alloy system) are necessary to accommodate all possible shape changes.

Since the martensitic phase can be deformed by either twinning or slip, there are two distinct yield points during a tensile test: a reversible and an irreversible. This is illustrated by the lowest of the three curves in Figure 2a ($T=M_s$). Deformation occurring after the first yield point and before the second occurs by twinning. Deformation after the second represents slip with the length of the plateau determined by the crystallography of the twinning process. The reversible yield stress is generally lowest at M_s (the martensite start temperature): twin boundaries become increasingly difficult to move at lower temperatures, whereas at higher temperatures the austenite is the stable phase, and the martensite must be stress induced. This stress needed to induce martensite increases linearly with temperatures above M_s (illustrated by the middle curve of Figure 2a). Eventually, however, the stress becomes greater than the irreversible yield stress and reversible deformation will no longer occur (upper curve in Figure 2a). This temperature above which one can no longer stress induce martensite is called M_d. These yield strength variations with temperature are summarized in Figure 2b.

The shape memory effect has been observed in many alloys, the seemingly necessary criteria being the occurrence of a martensitic transformation whose geometric accommodation takes place by either twinning or faulting. Out of the many shape memory alloy systems, only the NiTi based and Cu-based have proven themselves to be commercially viable materials with useful engineering properties. However, ongoing research is revealing promising candidates such as FeMnSi [16-19] and NiAl [20-22] which may soon extend this list. Comparing the NiTi and Cu-based materials, NiTi has advantages in strength, corrosion resistance, electrical resistivity and fatigue resistance. Furthermore the austenitic phase in the warmer NiTi alloys is essentially stable with respect to diffusional phase transformations, whereas rapid quenching is usually required in

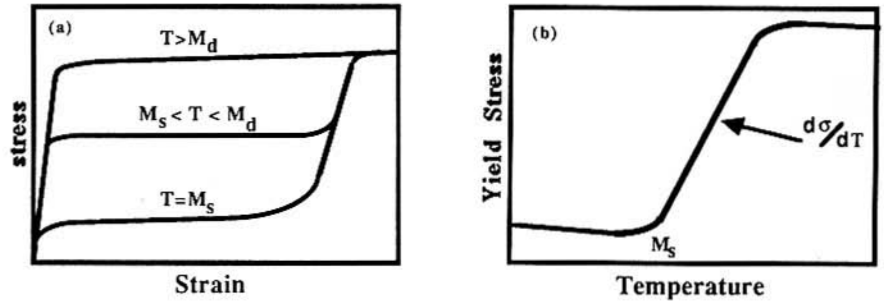


Figure 2: (a) Typical stress strain curves at different temperatures, and (b) the dependence of yield strength on temperature.

Cu-based alloys. Two commercial Cu-based alloy systems exist: CuAlNi and CuZnAl. CuAlNi is the stronger and more stable, but is often brittle, particularly if measures are not taken to control grain size. One clear technical advantage of Cu-based alloys is that substantially higher transformation temperatures can be achieved compared to NiTi alloys: M_s temperatures above 200°C have been reported in CuAlNi, whereas 90°C would appear to be the practical limit in NiTi. (Transformation temperatures above 450°C can be obtained in NiTi by making large additions of Pd [23-24], but it appears more appropriate to classify these alloys as TiPd with additions of Ni.) In NiTi a third phase called the R-phase is often observed prior to martensite formation. The R-phase has many characteristics of the martensite including internal twins, no volume change, a stress-strain plateau, and a shape memory effect of 0.5 to 1.5% [25-30]. As will be pointed out there are some unique aspects of the R-to-austenite memory which can be quite useful.

FREE RECOVERY

Free recovery is the simplest of the four shape memory events, consisting of a deformation below M_s and then heating to recover the original shape. A schematic description is shown in Figure 3, the stress-strain perspective better illustrating the deformation process and the strain-temperature perspective better illustrating recovery. Some key descriptors of the event shown in Figure 3a are the total deformation strain (ε_t), the plastic strain (ε_p), and the amnesia, or final strain (ε_f). Implicitly defined is the recovery strain (ε_r). Figure 3b shows three more parameters, the austenite start and the finish temperatures (A_s and A_f), and the deformation temperature, T_d. This Figure represents the general case, where ε_t is large, and may not be completely recovered during heating; for small deformations, there is no appreciable amnesia.

Figure 4 shows an example of the data that might be needed to design using the free recovery event: in this case, the relationship between the total deformation strain, springback strain, recovery strain, and amnesia. As the total strain increases, so do the plastic and amnesia strains; the recovery strain increases with total strain until some maximum (8% in the case of polycrystalline NiTi) beyond which irreversible slip processes begin to interfere with the reversible twinning process. In many copper based alloys, low ductility causes the material to fracture before the maximum recovery strain is reached. In fact it is difficult to achieve more than 4% free recovery in polycrystalline CuZnAl and 3% in CuAlNi.

There are few practical uses of the free recovery event, one celebrated exception being the space antennae [32,33]. Others, such as a heat activated eyeglasses, and brassieres [34] have been proposed, but seem to be better suited for pseudoelasticity, as will be described later. Still other applications thought originally to be "free" recoveries, are in fact not entirely free of an opposing stress and need to be considered as actuators.

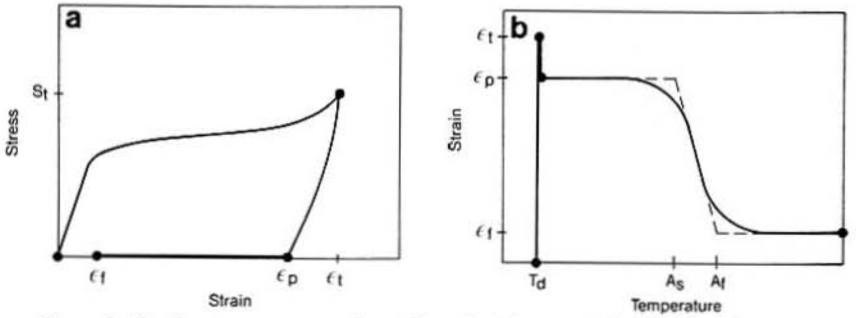


Figure 3: The free recovery event shown from the (a) stress-strain and (b) strain-temperature perspectives.

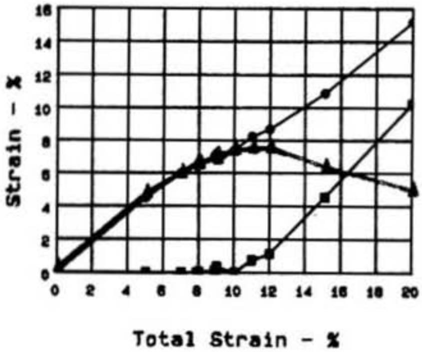


Figure 4: Relationship between total strain and the amnesia (■), recovery (▲) and plastic (●) strains. (Data is from a cryogenic NiTiFe alloy.)

The most important questions to ask when screening a free recovery application are:

1. What transformation temperatures are required and are they within the range of our current alloys? A_s temperatures must be below 110°C in NiTi and below 200°C in copper alloys.
2. How much strain is required? Strains over 8% are impractical for NiTi, with 2-4% being the limit for copper based alloys.
3. Will a small two-way effect hurt the product performance? Cooling most alloys below M_s will result in a slight reverse movement towards the original deformation. Thus a wire intended to recover the shape of a flower, for example, may retain that shape only as long as it is held above M_s.
4. Does the application require proportional control (i.e. a unique relationship between strain and temperature)? If so, hysteresis might be a problem and a bimetal the preferred choice.

CONSTRAINED RECOVERY

Constrained recovery is best visualized by imagining a solid, perfectly rigid pin, and a shape memory ring with an inside diameter slightly smaller than the pin. The ring is expanded in the martensitic state and placed over the pin. As it is heated, the ring freely recovers until it contacts the pin, which prevents full recovery and generates a stress. Whereas the function of the memory alloy during free recovery was to produce a strain, the function here is to develop a stress. Schematically, this is shown in Figure 5. As before, the event is multi-dimensional, and should be viewed in three planes; stress-strain, stress-temperature and strain-temperature. Two additional parameters appear in the stress-strain perspective (Figure 5a), the contact strain (ε_c) and the recovery stress (σ_r). Figure 5b shows the free recovery portion of the event and the contact temperature T_c. In Figure 5c, the stress rate ($d\sigma/dT$) and M_d are shown. The stress rate is constant and can be derived theoretically from the Clausius-Clapeyron equation [34-40]. Typical values for this very important property (in MPa/C) are between 4. and 20. for the martensitic transformation in NiTi (30. to 70. for the R-phase) and 2. to 5. for brass. M_d (defined earlier as the temperature above which martensite cannot be stress induced), is indicated by the leveling of the stress-temperature curve in Figure 5c.

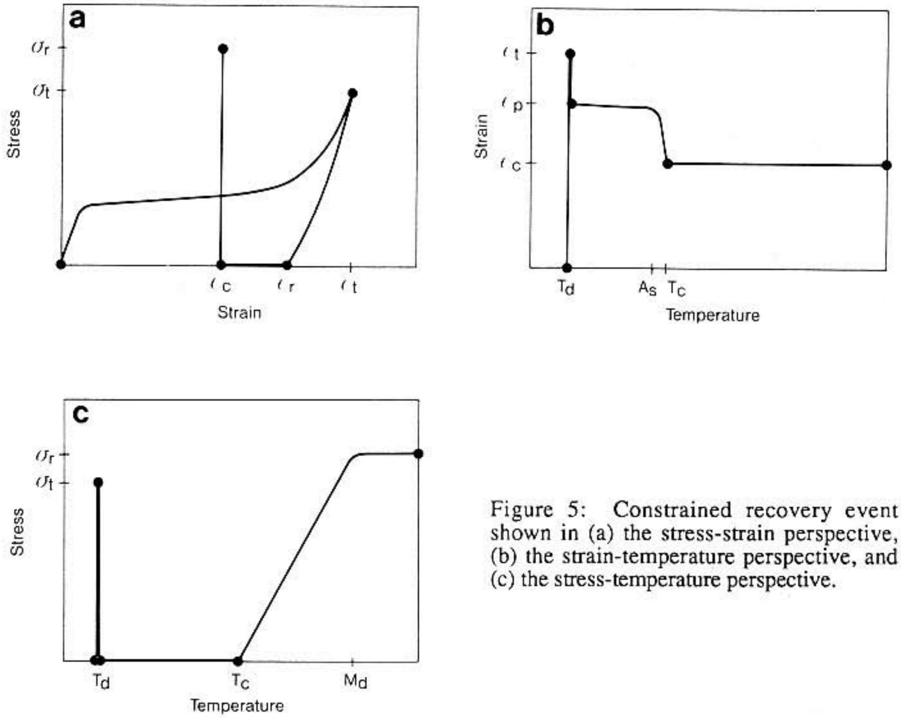


Figure 5: Constrained recovery event shown in (a) the stress-strain perspective, (b) the strain-temperature perspective, and (c) the stress-temperature perspective.

Figure 6 shows typical values for recovery stresses in NiTi, which have been measured to be anywhere from 350 to 900 MPa depending upon the alloy and condition [41-49]. Figure 6 also shows that recovery stress generally increases with contact strain, implying that low contact strains are to be avoided. So although an alloy may have 8% "free" motion, only 6% is usable if a dependable stress level is required. Note that the general envelope of Figure 6 resembles an austenitic stress-strain curve. In fact they do not overlay. The stresses developed during recovery typically fall 10-15% below the isothermally measured austenitic tensile curve [44,47,48,49].

The above description relates to constraint by an absolutely rigid substrate with the same coefficient of thermal expansion as the memory material. More often, the substrate deforms, either elastically or plastically. In the case of a pipe coupling, the pipe is crushed during recovery and the path is controlled by the mechanical properties of the pipe. Moreover, differential thermal expansion reduces the interference stress by: $\Delta\sigma = E\,\Delta\alpha\,\Delta T$. Predicting recovery stress is therefore more difficult than simply constraining a tensile specimen and heating; measurements must be made dynamically, by enforcing a particular stress-strain path to represent substrate deformation and a particular strain-temperature path to represent differential thermal expansion [49]. As an example, Figure 7 shows the stresses developed during recovery against a linear-

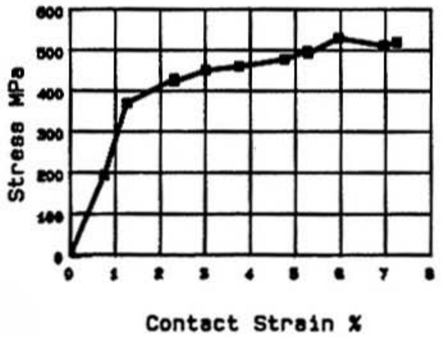


Figure 6: Stresses developed in a cryogenic NiTiFe alloy by rigid contraint at various contact strains.

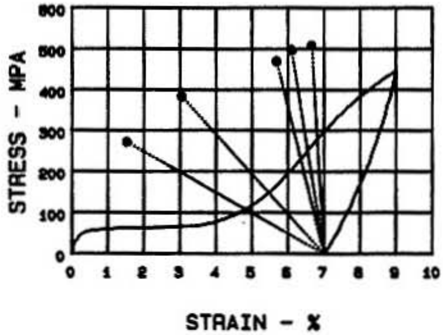


Figure 7: Stresses developed in a NiTiFe alloy by elastically constraining at five different compliances.

elastic substrate while compensating for the thermal expansion effects on strain. As one would expect, greater substrate compliance leads to lower recovery stresses, but the envelope of recovery stress values falls well below the envelope for rigid constraint (Figure 6). Thus recovery stress is a path dependent property.

To date, applications described by the constrained recovery event have been the most successful type of shape memory application. Some examples include:

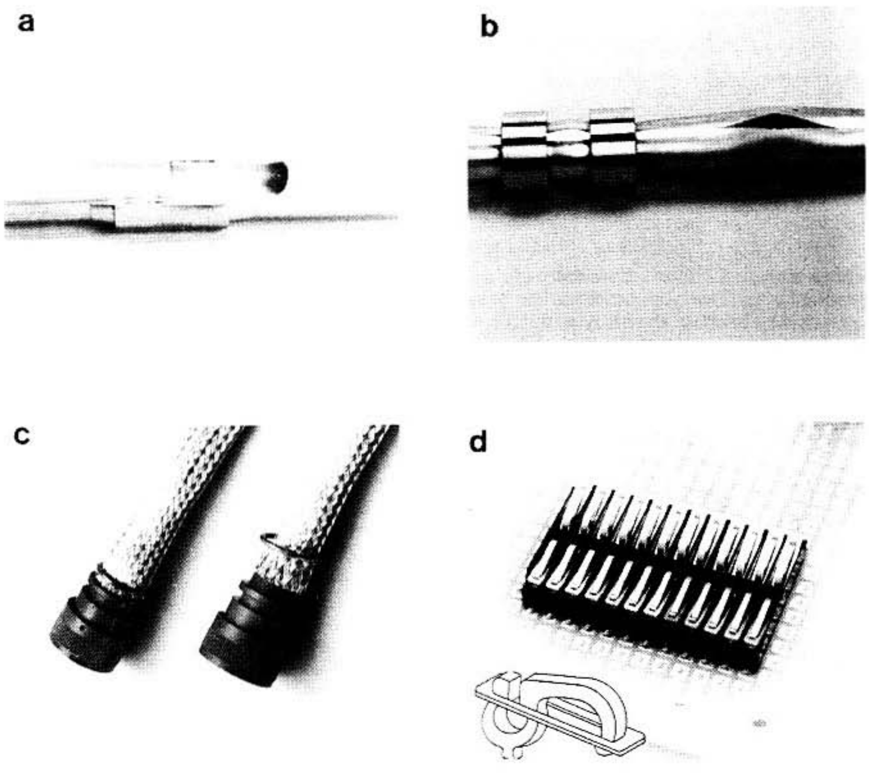
1. Tube and pipe couplings [50-62]. Sleeves are fit around tube or pipe and shrunk to make extremely easy, fast and reliable joints (Figures 8a and 8b).
2. Fasteners [63-66]. Memory rings are used to fasten braided shielding to electrical connectors, to fix bearings on shafts, to fasten two dissimilar materials (such as a ceramic to a metal), etc. (Figure 8c).
3. Electrical connectors [67-77]. These contacts have zero insertion forces, high retention forces, and are very compact, making them well suited to high pin density connection problems (Figures 8d and 8e).
4. Pipe repair sleeves. Sleeves can be inserted into, or be shrunk onto, a pipe for repair or surface protection. The memory metal may press a polymeric sleeve against the surface or may seal directly against the pipe.

Stable NiTi based alloys are generally preferred in constrained recovery applications for several reasons: larger recovery strains (critical to maintaining sufficient unresolved recoveries on normal substrate tolerances), high resistance to stress corrosion cracking, greater thermal stability, and high ductility. For some price sensitive and low performance applications, Cu-based alloys have been successfully used. If an installed memory coupling is cooled near its transformation temperature, it will relax or even open. Thus constrained recovery applications have traditionally required cryogenic alloys so that components would remain austenitic over a sufficiently large temperature range. Recently, however, it has become possible to introduce a large hysteresis in certain NiTi alloys, making it possible to store expanded parts in their martensitic state at room temperature, but remain fully austenitic to -100°C after recovery [78-80]. This capability is available to a lesser extent in some Cu-based alloys by exploiting the martensitic stabilization process [81-83].

In screening constrained recovery types of applications, two questions should be immediately asked:

1. What are the tolerances of the parts to be joined? Only a 6.5% range of contact strain is available with NiTi, which must account for the machining tolerances of the coupling, the gap needed for easy installation, any crushing or deflection of the substrate that may occur, and the tolerances of the parts to be joined. For 8mm nominal tubing, for example, the actual tube diameters typically must be within ± 0.1mm to allow shape memory joining.
2. What is the temperature range of the memory element? Parts in service must remain at least

above M_S (keeping in mind that M_S is increased by $\Delta M_S = \sigma_r (d\sigma/dT)^{-1}$) and below 360°C (the temperature at which stress relaxation becomes a problem in NiTi [84-88]). Stresses in brass couplings begin to relax at temperatures as low as 100°C.



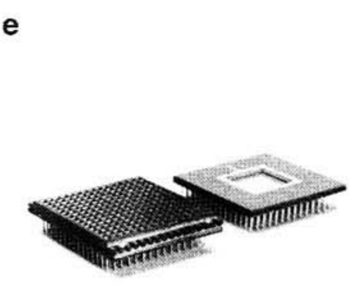


Figure 8: Products utilizing the constrained recovery function: (a) cut-away of a cryogenic NiTi hydraulic coupling in the aerospace industry, (b) a commercial coupling using two heat-to-shrink NiTi rings to crush a stainless steel liner (note that the mode of failure was pipe burst, not coupling failure), (c) a welded NiTi wire ring used to attach braided shielding to an electrical connector backshell, (d) Cryotact electrical connector as used in Dual In-Line Packaging (the inset drawing shows the NiTi rectangular ring and CuBe contact) and (e) a Pin Grid Array Package connector.

ACTUATORS

The third branch of applications includes those that move against a resisting force. Visually, one can imagine a wire of memory metal fixed at one end and a weight hanging from the other; the wire is stretched by the weight in the martensitic state and will lift the weight when heated. When again cooled, the weight will stretch the wire (assuming, of course, the mass is correctly chosen). In this case, the system is self-resetting and the event can be performed repeatedly. Most applications of this nature are, in fact, cyclic.

Schematically, the event is modeled in Figure 9. Again we deform and unload just as in the first two cases. We then apply a constant load (σ_0) and begin heating. Key descriptors are the martensitic strain (ε_m) the austenitic strain (ε_a) and the recovery strain (ε_r=ε_m-ε_a). As pointed out above, subsequent cooling may again deform the memory metal, though not necessarily to ε_m. The motion on cooling occurs at the M_s and M_f temperatures. The first segments (deformation and unloading) are referred to as prestraining, and of course can be skipped by loading directly to σ_0. Figure 10 shows that the transformation temperatures (A_s, A_f, M_s and M_f) all increase linearly with the applied stress at a rate given by the stress rate ($d\sigma/dT$) of the material.

The shape memory event shown in Figure 9 does work since there is a displacement against a force. Figure 11 shows how recovery strain and thus work output of NiTi depend upon the resisting stress. The work output is low at small stresses since the force term is small, and low at high stresses because the alloy is unable to displace the high resisting force. Such curves are important in optimizing the use of memory material. Fatigue is also a key issue in most applications of this sort, making cyclic work outputs significantly lower than the single cycle values shown in Figure 11. A fatigue failure in a conventional metal is often defined as fracture. In a shape memory alloy, however, there are many modes of failure: an unacceptable shift in the transformation temperatures, a reduction in the stroke or recovery strain, or ratcheting [89-93,117]. Ratcheting is defined as a migration of the austenitic strain and progresses nearly logarithmically with the number of cycles. Fatigue life can be strongly influenced by heat treatment, alloy selection, and design [92-98]. Due to the complexity and definition inconsistencies in defining a fatigue failure, there is a wide variation in reported fatigue lifetimes [99-103]; moreover there are indications that fatigue life is path dependent: knowing the stress and strain limits is not sufficient, one must in addition know the path taken between the end points [104]. There is also now evidence that fatigue damage can be substantially reduced if operation is limited to using only the R-phase↔austenite transformation [98]; even though this substantially reduces the work output, the extended lifetime and the reduced hysteresis and latent heat may be preferred in some cases. At this time the fatigue aspects of actuators cannot be generalized; each situation must be considered by itself.

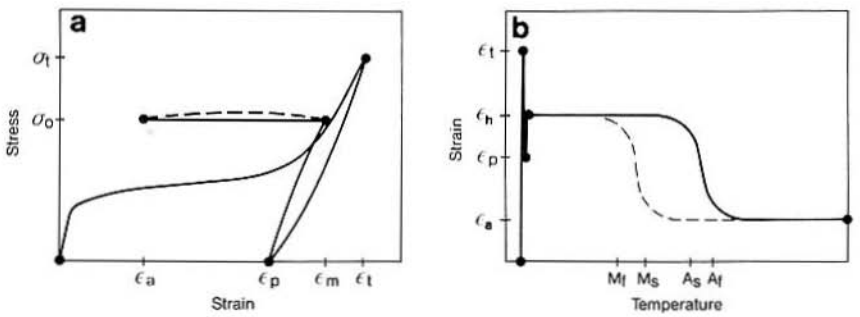


Figure 9: Schematic representation of an actuator, or the work generation process shown in the (a) stress-strain and (b) strain-temperature perspectives.

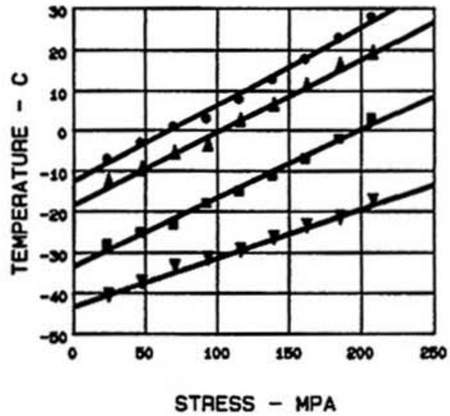


Figure 10: Transformations temperatures of a CuZnAlMn alloy are shown to increase linearly with stress according to $d\sigma/dT$, as shown in Figures 2b and 5. Shown are M_s(■), M_f(▼), A_s(▲) and A_f(●).

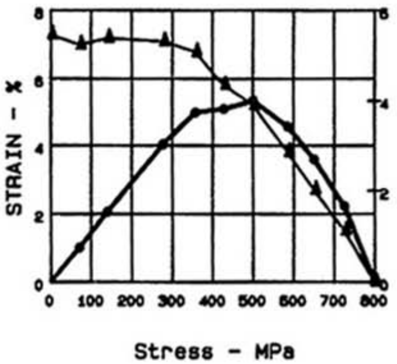


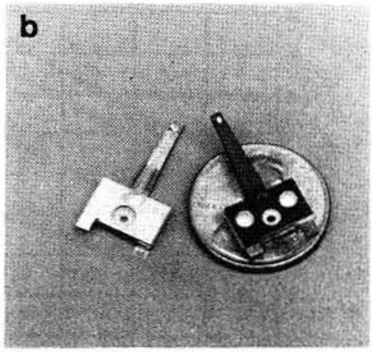
Figure 11: The recoverable strain (▲) and the work output capacity (●) for a work hardened NiTi-based alloy. Maximum efficiency would be against an opposing stress of 500 MPa.

Actuators are generally divided into two categories: electrical and thermal. These two types of device will be considered separately since they differ both with respect to critical design considerations and alloy selection criteria.

Electrical actuators are generally competing with solenoids or servo-motors. Their function is simply to move an object or perform a task on demand. A current is passed through the memory alloy, internally heating it above A_s to recover its shape. Examples would include a remote louvre opening device [105], (Figure 12a), head lifters for disc drive units [106], (Figure 12b), door latches for cars (Figure 12c) and robotic devices [107-111]. In all cases, the task could be done using a servo-motor, but shape memory provides advantages of compactness, quietness, and simplicity. In most electrical actuators, the system is expected to reset itself for repeated use; this is generally accomplished using a conventional "biasing" spring which is elastically deformed by the shape memory device during heating, but in turn deforms the memory alloy during subsequent cooling. Most actuator designs also require overload protection, so that if the memory alloy is prevented from recovering (due to ice formation on the louvres of Figure 12a, for example) the device will not be plastically deformed and destroy itself.

Because of their high electrical resistivity and longer fatigue life times, NiTi alloys usually have a substantial advantage over Cu-based alloys in these applications. In reviewing potential electrical actuator applications, the following questions should be asked,

1. What reset times are required? It is generally possible to heat and actuate very quickly; but to cool and reset is usually slow. Although reset times can be improved through intelligent designs, memory actuators may never cycle as quickly as servo-motors. This is particularly a problem for many robotic applications.
2. What fatigue lifetimes are required? As pointed out, fatigue is a complicated issue, but for applications requiring over 100,000 cycles, the work output per cycle must usually be reduced to the point where shape memory is seldom the best actuation method.
3. What will ambient temperature be? The current needed to actuate will depend upon the ambient temperature. Moreover, if ambient temperature approaches A_s or M_s, the device could self-actuate or fail to reset.



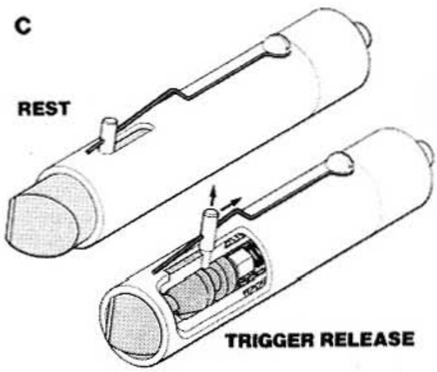


Figure 12: Examples of electrical actuators include: (a) a device to open protective louvres on automobile fog lamps, (b) a disc drive head lifter and (c) an automobile door latch.

Thermal actuators are generally in competition with bimetals, their function being both to sense temperature and to do work. Memory alloys have significantly greater motions and work outputs than do bimetals, and can delivery their motion in any form (tension, bending, torsion, etc.). Bimetals, on the other hand are hysteresis-free and exhibit linear motions over a wide temperature range. Examples of applications would be various fire protection devices [112], window opening devices (Figure 13a and 13b) [113-116], anti-scald shower heads, air conditioning vent deflectors, circuit breakers [117] (Figure 13c) and a variety of others [118-123]. The proper choice of a thermal actuator alloy is not clear. The brasses and bronzes remain the only practical alloy for high actuation temperatures (over 100°C), but are prone to stress corrosion, instability and poor ductility . In most of these applications, shape memory is directly competing with bimetals [124-125] making cost another important alloy selection issue. NiTi has the advantage of the essentially hysteresis-free R-phase transformation, but there are limitations: small recovery strains (maximum 1.0%), a relatively narrow temperature range over which the effect can be observed (-40 to 50°C), and susceptibility to damage from excessive heating or cooling. There is at least one commercially successful thermal actuator using the R-phase: a device for controlling the louvres in an air conditioner [120].

Some of the key questions which should be asked regarding thermal actuation would be:

1. Can the application tolerate a hysteresis? In most cases, a normal martensite-austenite hysteresis of 30°C is unacceptable. Proportional control, where position is uniquely identified with temperature, is currently impossible with shape memory unless the R-phase is invoked.
2. What actuation temperatures are required? NiTi is useful up to 90°C. Cu-based alloys can be used to 150°C, but only if lengthy excursions above that are unlikely and if the environment is inert. Accuracy is also an issue with Cu-based alloys, since the transformation temperatures can change significantly with exposure and fatigue [81-83].

3. What fatigue lifetimes are expected? Though the duty cycles are generally less demanding than in electrical actuation, fatigue can still be a factor.

Several operational shape memory motors and pumps have been built [126-130], but are not close to becoming a commercial success. Fatigue and inefficiency are the key factors. To maximize work output and keep costs low, high stresses must be designed into the device, causing unacceptable fatigue lifetimes. Moreover, the hysteresis and the high heat of transformation associated with the martensite-austenite transformations lead to low efficiencies; although there continues to be a large range in reported efficiencies, the consensus [131-144] would seem to put it at roughly 2%. There is at least one commercially available demonstration engine that uses the R-phase↔austenite transformation instead of the martensite↔austenite [145]; this dramatically decreases losses from the hysteresis and the heat of transformation, but also decreases the memory strain and mechanical work output.

Finally, some applications require that the event is resetting with no load or biasing spring. This requires that the material has a two-way effect. Two-way effects are easily obtained in both Cu-based [117,146-149] and NiTi alloys [150-153] but fatigue and stability issues are incompletely understood: alloys and conditions exhibiting the greatest two-way effects are not those with the highest work capacity and fatigue resistance. There are many possible training sequences to induce the two-way effects, but all are complex [154-166] and at least in many cases can be erased by modest overheating (to 250°C) [167]. With our current knowledge base it seems advisable to avoid relying on the material to reset itself, but instead to use an additional resetting or biasing spring. One special case of the two-way effect, called the All Round Shape Memory Effect (ARSME), can be obtained by ageing Ni-rich NiTi alloys while constraining them in bending. This method has been demonstrated to introduce two-way effect in the R-Phase transformation, and thus deliver a reversible, essentially hysteresis-free memory [168-176]. One major drawback is that the microstructural mechanism requires inhomogeneous and hydrostatic stresses, so torsion, tension, and compression modes do not seem compatible with ARSME.

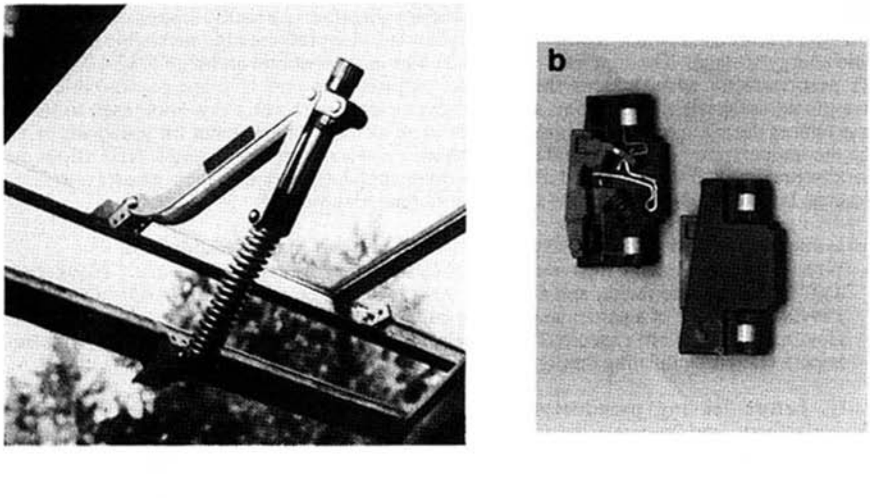


Figure 13: Examples of thermal actuators include (a) a greenhouse window opener using a CuZnAl alloys which automatically opens and closes windows at certain temperatures without any electrical connections and (b) a thermally driven circuit breaker. (Figure 13a is by courtesy of Memory Metals Inc.)

PSEUDOELASTICITY

The fourth type of shape memory event is isothermal and can be completely viewed in the stress-strain plane. When a shape memory alloy is deformed above A_s and below M_d, martensite is stress-induced. During unloading, the martensite again becomes unstable and the material reverts to its original shape (Figure 14). σ_l is the transformational stress upon loading (the stress needed to start the transformation to martensite) and σ_u is the transformational stress upon unloading (corresponding to reversion back to austenite). In practice it is more useful to define these as the inflection points in the loading and unloading plateaus instead of using the standard offset methods. The stress hysteresis ($\sigma_l - \sigma_u$) can be related through the stress rate to the temperature hysteresis during loaded recovery. The material is elastic since it returns to it original shape upon unloading, but because the behavior is non-linear, it is called pseudoelastic (or superelastic).

The function of the memory metal in the pseudoelastic event is to store energy. Listed below are the springback strains and stored elastic energies (as defined by $\int \sigma_u \, d\varepsilon$) for high performance spring materials:

Material	Maximum Springback Strain	Stored Energy
Steel	0.8%	8. Joules/cc
Beta Titanium	1.7%	14. Joules/cc
Pseudoelastic NiTi	8.5%	42. Joules/cc

This, however, is a single cycle, isothermal event - an ideal scenario for shape memory and one seldom found outside the laboratory. Consider first the isothermal condition. Figure 15 shows the response of a pseudoelastic material to changes in temperature: stress continuously changes according to the material stress rate and the permanent set is low over a rather limited temperature range (80 degrees, in the case of NiTi). Though the cyclic properties of pseudoelastic materials have not yet been fully defined, there can be substantial "walking" or ratcheting as it goes through the transformation cycle [177-181].

Applications using the pseudoelastic event are therefore currently limited to low cycle, isothermal situations in which geometric or weight restrictions require high reversible motions or elastic energy storage. The first such application was as orthodontic archwire [182-186] where NiTi pseudoelastic wire reduces the need for adjustments and is more comfortable than conventional materials (Figure 16a). A second example (Figure 16b,) is a hook used to locate breast tumors during surgery. The body appears to be an ideal environment for pseudoelasticity since the temperature is well controlled and requires a biocompatible material. NiTi alloys are generally preferred to the Cu-based alloys for these applications due to their greater corrosion resistance, larger pseudoelastic strains and longer fatigue lifetimes.

In reviewing potential pseudoelastic applications, two questions should be addressed:

1. What is the temperature range over which pseudoelasticity is expected? Typical alloys cover a 40°C temperature range, and although this range can be moved from -100 to +100 by alloying, the range of a particular device is unlikely to be over 40°C.
2. How many cycles are expected? Pseudoelastic recovery is generally imperfect, with the imperfection accumulating during repeated cycling.

Finally, before leaving pseudoelasticity it should be noted that although the terms "pseudoelasticity" and "superelasticity" are used interchangeably, it may be more appropriate to consider superelasticity the more general term referring to all mechanisms which provide very high elastic ranges (over 3%), and to reserve the word "pseudoelastic" to describe the subset that also exhibit non-linear unloading behaviors. For example in NiTi it appears that more than 4% linear superelasticity can be achieved by neutron irradiation or by cold working in a controlled way [187,188]. Although this property is interesting and potentially useful, it is not yet well enough understood to be used in product design.

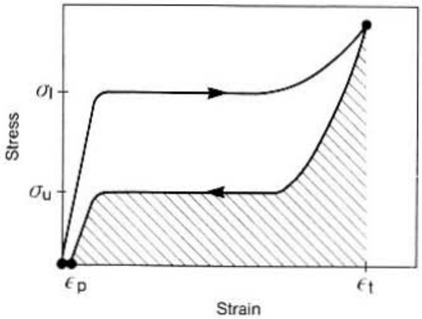


Figure 14: Schematic representation of the pseudoelastic event shown in the stress-strain plane.

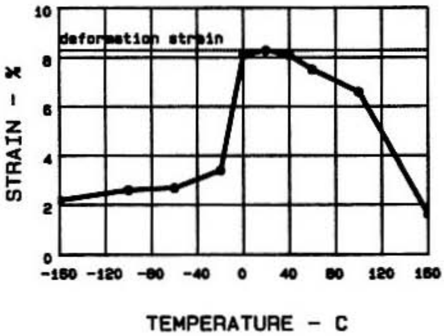


Figure 15: Springback strain (strain recovered during unloading) shown as a function of temperature after deforming a pseudoelastic 50.8 at.%Ni-Ti wire 8.3% in tension.

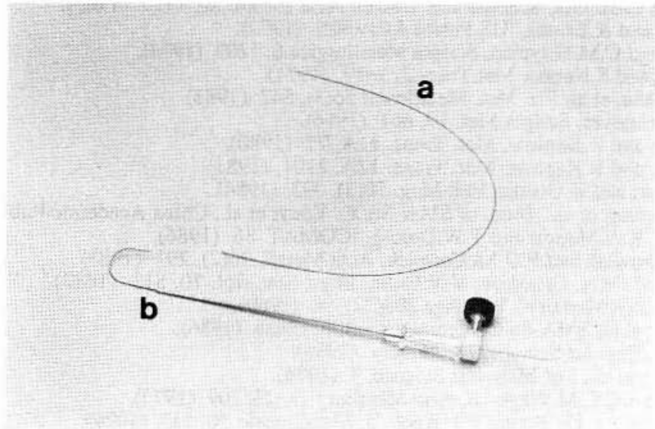


Figure 16: Examples of pseudoelastic products include: (a) orthodontic archwire and (b) a surgical localization hook. (Courtesy of Mitek Surgical.)

CONCLUSIONS

Four basic types of shape memory event have been discussed: free recovery, providing motion or strain; constrained recovery, generating a stress; actuators, providing kinetic energy and work; and pseudoelasticity, storing potential energy storage. It is clear that each is individual in terms of function and application potential. Together they encompass applications as different as springs for dentistry, large pipe couplings, circuit breakers, and head lifters for magnetic disks. Of all these applications only the pipe couplings and orthodontic arches, can currently be considered a proven "high volume" applications. It remains to be seen which other areas will be successful. One factor that will clearly affect this will be costs. Although the Cu-based alloys are theoretically less costly than NiTi, this is seldom an important alloy selection criterion; raw material costs are still a very small part of the total cost of a fully engineered device.

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