Chapter 5

Shape Memory Alloys — A Smart Technology?

Neil B. Morgan and Clifford M. Friend
Department of Materials and Medical Sciences,
Cranfield University,
Shrivenham, Swindon SN6 8LA, UK.

5.1 Introduction

Shape memory alloy (SMA) is the generic name given to alloys which exhibit the unusual property of a strain-memory which can occur either at constant temperature, where large yet recoverable strains are possible (superelasticity), or on changes in temperature, where apparently permanent strains can be fully recovered (thermal shape memory).

These memory effects have their origin in a particular type of phase transformation (change in internal crystal structure) which produces a microstructural constituent known as martensite. A martensitic transformation is displacive, that is it occurs through a shearing of the crystal structure from the so-called parent-phase to that of the martensite. This is illustrated schematically in the two-dimensional analogue shown in Fig. 5.1. Such transitions are diffusionless, resulting in no change in chemical composition, and form the basis of heat treatments in many metallic materials, including the familiar transformation of austenite to martensite in ferrous (iron-based) alloys. Thermally induced martensitic transformations occur over a falling temperature interval (Fig. 5.2). The transformation proceeds at the M_s (martensite start temperature) where the martensite phase first appears, and progresses athermally (occurring over a falling temperature interval)

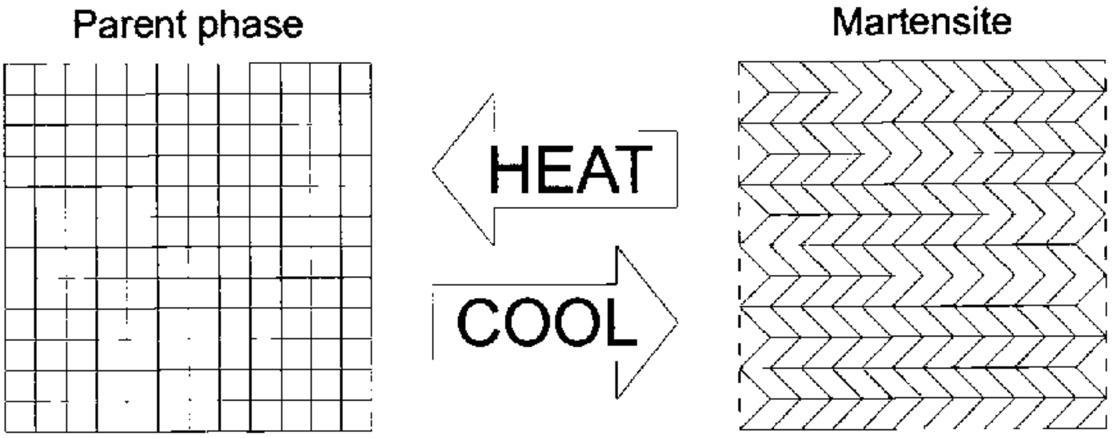

Fig. 5.1 Two-dimensional, two-variant analogue of a thermoelastic martensitic transformation.

until at the M_f temperature transformation is complete. On heating, at the A_s temperature the last martensite formed during forward transformation begins to revert to parent-phase, and there is then continuous reversion until at the A_f temperature the high temperature parent-phase is fully restored. The overall hysteresis between forward and reverse transformation pathways in SM alloys is small, usually between 10 and 50°C; a behaviour quite different to that exhibited by non-thermoelastic martensitic transformations, typified by steels. Thermoelastic martensitic transformations, which form the basis of SMA behaviour, can be repeated indefinitely as long as high temperature excursions are avoided.

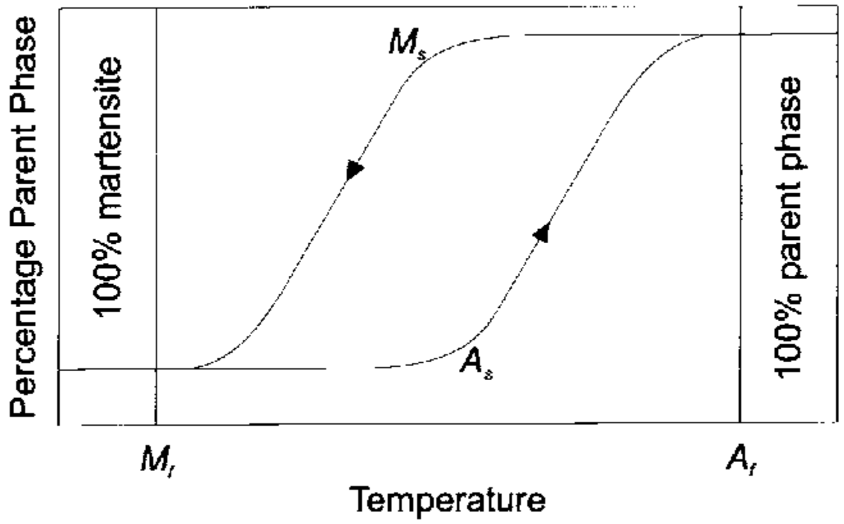

Fig. 5.2 Hysteresis curve for a thermoelastic martensitic transformation.

5.2 Structural Origins of Shape Memory

A feature of all martensitic transformations is that there are a number of equivalent shear directions through which the martensite can form within a region of parent-phase. This results in the formation of martensite *variants* within the microstructure of a transformed alloy. This is illustrated again schematically in Fig. 5.1 using a two-dimensional, two-variant model. This figure shows two crystallographically equivalent martensite variants created by different atomic shears from the parent phase. In this analogue the two opposite shears maintain the macroscopic shape of the crystal block (represented by the dotted line). Such a microstructure, where the shear of one variant is accommodated or "cancelled" by that of the other, is known as a self-accommodated structure. This process forms the basis of the shape memory effect in SMAs, although three-dimensional self-accommodation requires a larger number of variants (typically up to 48 in many alloys).

It is apparent from the two-dimensional analogue in Fig. 5.1 that the parent phase of a SMA has higher symmetry than the martensite. This means that although there are many transformation routes through which the martensite can form from the parent phase, there are only a few possible routes for the reverse transformation; often limited by other factors to a single reversion pathway. In other words transforming to martensite and reverting to parent phase results in a complete restoration of microstructure (Fig. 5.1). In SMAs the interfaces between martensite variants are glissile (mobile) and their positions can be influenced by external variables; perhaps most importantly by applied stress. This is illustrated in Fig. 5.3 where the positions of the martensite interfaces change under the influence of stress/strain, creating a balance of variants whose shears best accommodate the direction of applied strain. That is the interfaces between variants move to "grow" the most favourably oriented variants and shrink the least. It is the ability to re-orientate martensite variants by the application of stress and to revert these to parent-phase which forms the basis of at least one shape memory phenomenon — the so-called one-way shape memory effect.

5.3 One-Way Shape Memory

Figure 5.4 schematically illustrates the macroscopic response of a one-way SMA. If such an alloy is deformed whilst in the self-accommodated marten-

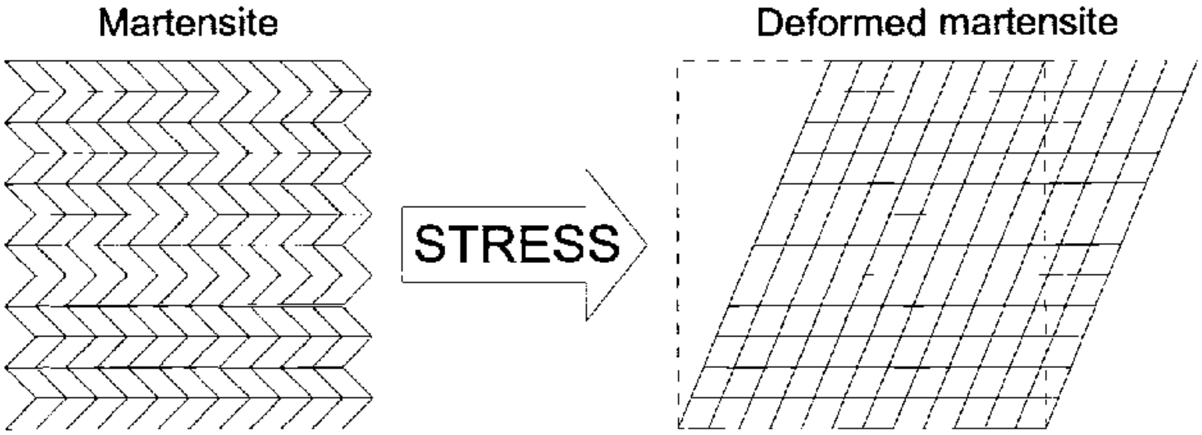

Fig. 5.3 Variant reorientation in thermoelastic martensites.

sitic state and subsequently unloaded, then an apparently permanent strain will remain. This is a result of the martensite microstructure being reoriented as shown in Fig. 5.3; the reorientation remaining on the removal of the external stress. If the alloy is then reheated to a temperature above the martensitic transformation temperature range then this apparently permanent strain will fully recover, returning the original macroscopic shape.

This is the so-called one-way memory effect. As long as the total strain does not induce permanent plastic flow, deformation may be of any type, e.g. tension, compression, bending or more complex combinations.

The internal structural changes that take place during the one-way memory effect can be visualised using the two-dimensional analogue in Fig. 5.5. Deformation takes place in the self-accommodated martensite

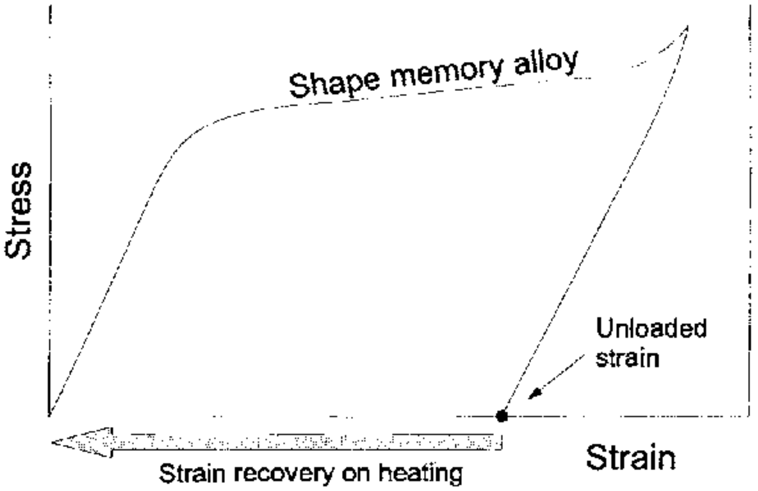

Fig. 5.4 Stress–strain behaviour during the one-way memory effect.

condition. During loading this structure becomes deformed through variant rearrangement, resulting in a net macroscopic shape change. When the alloy is unloaded this deformed structure remains, resulting in an apparent permanent strain. However, if the alloy is now reheated to a temperature above the martensitic transformation range the original parent phase microstructure and macroscopic geometry is restored. This is possible because no matter what the post-deformation distribution of martensite variants, there is only one reversion pathway to parent-phase for each variant. When the alloy is subsequently cooled to below the transformation range a self-accommodated martensite microstructure is formed and the original shape before deformation is retained. Thus a one-way shape memory is achieved. The maximum strain recovered through this process depends on the shape memory system, however, it is typically in the range 1–7% for polycrystalline alloys.

5.4 Two-Way Memory Effect

During the one-way memory effect only one shape is 'remembered' by the alloy; the so-called hot (parent phase) shape. However, SMAs can be processed to remember both hot and cold shapes, thus exhibiting a two-way memory where the component can be cycled between two different shapes without the need for an external stress.

Two-way shape changes rely entirely on microstructural changes during martensitic transformation which occur under the influence of internal stress [1]. Self-accommodation of the martensite microstructure is lost in the two-way effect due to the presence of these internal stresses, and predominant variants form during transformation (i.e. there is an excess of certain variants within the martensite microstructure compared to self-accommodated structures). This results in a shape change towards the cold-shape on cooling and towards a second hot (parent phase) shape on heating through the reverse transformation. This cycle is also illustrated in Fig. 5.5. Notice how the self-accommodated structure is missing in such alloys and that the martensite shape is achieved directly by cooling below the M_s temperature under the influence of internal stress. Internal stress may be introduced in a number of ways, usually referred to generically as "training". These sites of stress must be stable on thermal cycling through the transformation and usually result from the introduction of irreversible de-

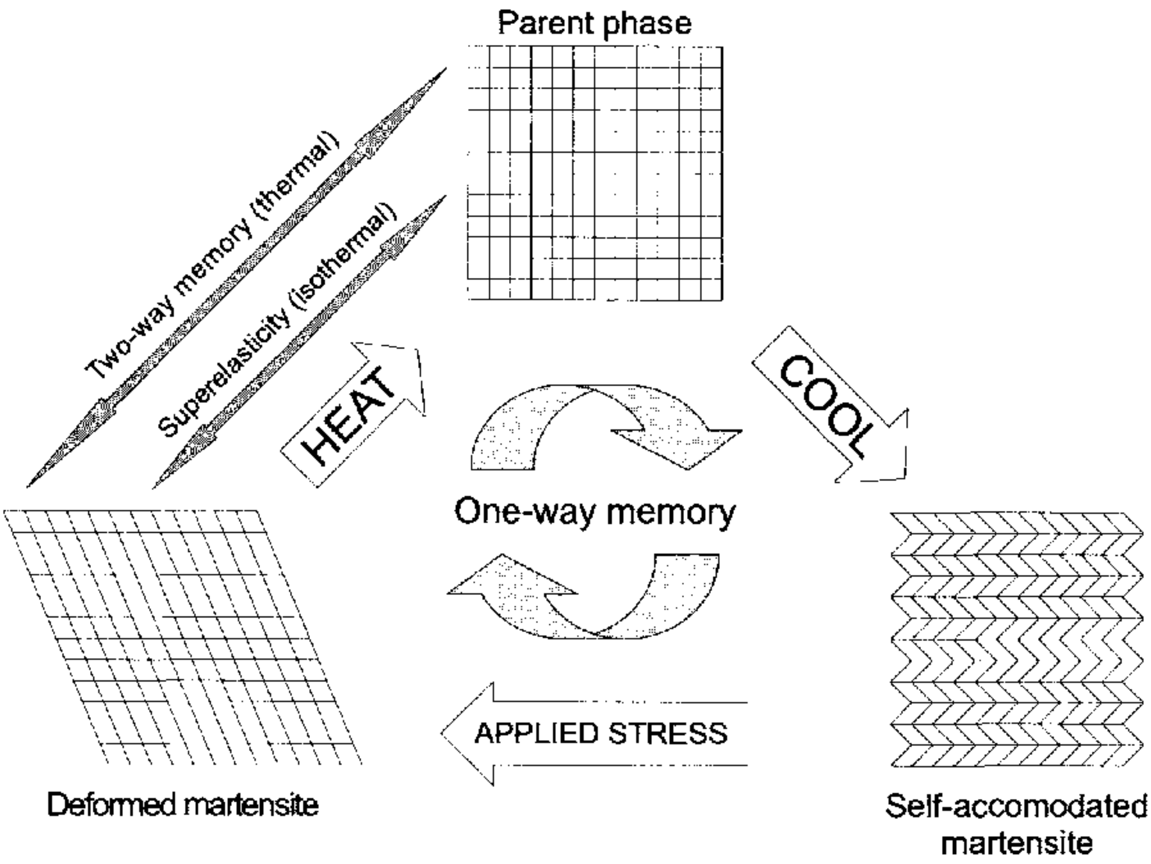

Fig. 5.5 Microstructural changes during thermal memory and superelastic phenomena.

fects. These are created by prior deformation [2; 3] or through the presence of particles and precipitates [4] created during special thermo-mechanical treatments [5]. Two of the most common training methods create two-way memory through the introduction of dislocation arrays and are achieved by:

- Cyclic deformation at a temperature below M_f followed by constrained heating in the cold-shape to a temperature above A_f.
- Cyclic deformation between the hot- and cold-shapes at a temperature above A_f [6].

5.5 Pseudoelasticity or the Superelastic Effect

When a SMA is deformed isothermally at a temperature above A_f, martensitic transformation can also be induced mechanically. The martensite formed in this way is known as stress-induced martensite (SIM). This is only stable under the application of stress, and on unloading, the reduction in stress and surrounding elastic forces generated during transformation cause the martensite to shrink back to the original parent-phase. Figure 5.6 shows the mechanical behaviour of such a superelastic material, and compares this to that of a conventional metallic alloy. Such superelastic materials can fully recover deformations up to 6–7% strain, depending on alloy type. It can be seen from Fig. 5.6 that superelastic deformation is also hysteretic, the upper plateau occurring during stress-induced martensitic transformation and the lower during reversion on unloading. It is both the large recoverable strain and constant recovery stress plateau that can be utilised in superelastic applications.

Figure 5.5 can also be used to explain the microstructural origin of these effects, with stress-induced transformation resulting in a predominant variant microstructure ("deformed martensite structure"), creating a macroscopic strain, which shrinks on reversion of the martensitic phase. The deformation hysteresis is also clearly associated with the inherent hysteresis of the underlying martensitic transformation (Fig. 5.2).

5.6 A Brief History of Memory Alloys and their Application

Arguably the first observations of shape memory behaviour were carried out by Ölander [7] in 1932 in his study of a "rubber like effect" in the Au–Cd system and by Greninger and Mooradian [8], 1938, in their study of Cu–Zn alloys. However, it was many years later that Chang and Read [9] first reported the term "shape recovery" whilst working on Au–Cd alloys. It was not until 1963, in a study on NiTi alloys, that Buehler *et al.* [10] first introduced the phrase "shape memory effect" as a material property. Indeed it was the discovery of the effect in these NiTi alloys that "kick-started" interest in shape memory applications. During the 1960s NiTi alloys and their early applications began to move the effect away from fundamental phenomena to useful engineering properties and fuelled international research. Duerig [11] divides the methods of harnessing thermal memory effects into three categories:

Free Recovery An alloy is apparently permanently strained and on the application of heat recovers its original shape; maintaining this during subsequent cooling. The function of the alloy element is therefore to cause motion or strain.

Constrained Recovery The alloy is prevented from full shape recovery thus generating stress on the constraining element.

Actuation Recovery The alloy is able to recover its shape but operates against applied stress, resulting in work production.

Duerig [11] also considers superelastic applications in the following way:

Superelastic Recovery The only isothermal application of the memory effect, superelastic recovery (also known as pseudoelasticity) involves the storage of potential energy through comparatively large but recoverable strains.

In some cases separation of the thermal and isothermal applications is not possible since many superelastic applications also involve free and constrained recovery (where the superelastic element either recovers its shape freely or is constrained by another mechanical element of a device). These terms therefore need not be confined to thermal effects. However, this broad type of categorisation is useful for conceptualising how shape change phenomena may be applied within engineering systems.

Although there are examples of NiTi SMA applications in all of the four categories described by Duerig [11], the greatest number have emerged in the area of superelasticity. Many excellent and unique devices have been constructed out of NiTi for the medical industry and this market is still growing at a considerable pace. It is perhaps, the reported biocompatability [12; 13; 14] allied to the less complicated design procedures for superelastic applications that has resulted in the high number of devices utilising this effect.

Guide wires for non-invasive surgery [15], orthodontic arch wires [16; 17] highly flexible surgical tools [18] and stents for the minimally invasive treatment of arterial and oesophageal strictures [19; 20] have all been successfully produced out of NiTi superelastic wires. In addition to the medical market, superelastic components are also successfully employed in consumer products such as spectacle frames [21] under-wired bras [22] and mobile phone antennae [23].

The three categories of thermal shape recovery have met with much less commercial success and are limited to just a few niche areas. Of these, perhaps the most successful is also one of the first. This is the coupling originally designed by the Raychem Corporation to employ constrained recovery for the joining of pipes in the Grumman F-14 aircraft [24]. In this application a ring of NiTiFe alloy is expanded in diameter at very low

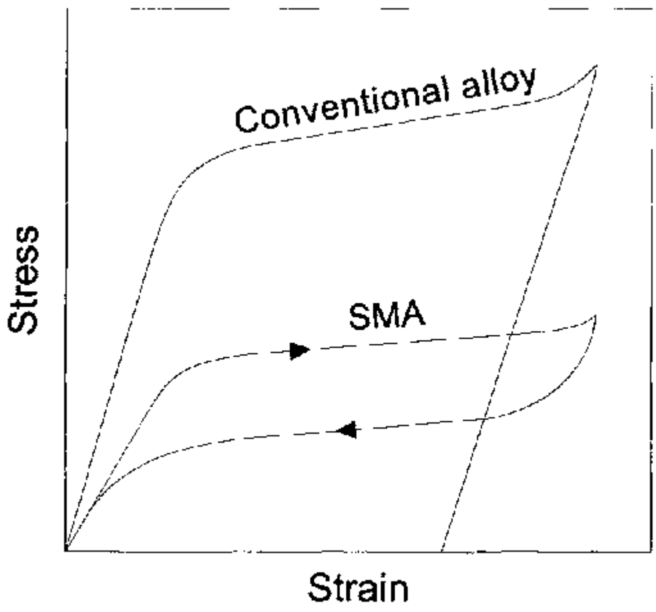

Fig. 5.6 Comparison of the stress strain curves of conventional and superelastic alloys.

temperatures and fitted over the coupling area of the pipes. As the ring returns to comparatively high ambient temperatures it attempts to contract to its original diameter and exerts high forces on the pipes resulting in very strong, reliable couplings. As well as pipe couplings SMAs have also been used in various electrical connectors and fastener applications, all utilising constrained recovery effects [25; 26].

Unconstrained recovery applications are few. Devices exploiting shape change only include fire protection devices and thermal cut out switches [27]. In these applications the alloy element acts as both thermal sensor and cut-out actuator and tend to be concerned with flow cut off valves. For instance the Proteus gas valve was specifically designed to cut off gas flow in the case of fire [28]. In this product a CuZnAl SMA spring expands at a particular temperature pushing a steel ball through a retaining ring. The valve can be reset manually at temperatures below the SMAs martensitic transformation and does not have to undergo repeated actuation or operate against constant loads.

The area of thermal shape change that perhaps has the greatest potential, for smart applications, is that of actuation [29; 30]. Many patents exist based on the principle of using a SMA element as a thermal actuator which converts electrical or thermal energy into mechanical work. However, because of the complicated design criteria for matching the desired motion, cycle life and actuation temperatures to an "off the shelf" material [31;

32] the number of successful repeatable actuation devices is limited. The devices that have met with commercial success are usually those that have been designed allied to stringent actuator research and development programmes. A good example of this is the air conditioner actuator developed by Matsushita Electrical Industrial Company Ltd. on the basis of the fundamental research carried out by Todoroki [33]. It is obvious, however, that the cost of this type of research is high and many SMA actuator designs do not get any further than the conceptual stage.

5.7 Why Not Use Bimetals?

This question is often asked of shape memory researchers and manufacturers when considering possible thermal actuator applications and deserves to be seriously answered. The answers are clear. The displacements of bimetallic strips tend to be much smaller than those of shape memory alloys and vary linearly with temperature, rather than the switch-like behaviour associated with SMAs over their relatively narrow transformation temperature range. In addition SMAs may be configured into many different shapes, e.g. a spring or tubular cross section, and exhibit a tailorable direction of deformation with temperature. Finally, and particularly important for thermal actuator applications, SMAs can exert recovery forces up to 100 times greater than bimetallic strips.

5.8 Types of Shape Memory Alloy

Despite a growing list of alloys that display the memory effect only copper-based and NiTi-based alloys have been commercially exploited, and by far the most important commercial shape memory alloys are those based on the NiTi system. It is their comparatively large shape memory properties and excellent corrosion resistance [34] that really sets these alloys apart in terms of commercial application.

In all SMAs careful processing and alloying permits close control of properties such as actuation temperature (phase transformation temperatures), strength and work outputs.

Copper-based shape memory alloys exhibit higher actuation temperatures (approximately in the range −200 to +200°C) than NiTi alloys and are sometimes the only choice for high temperature applications, (i.e. > 100°C).

The practical recoverable strain in polycrystalline copper-based SMAs also ranges from approximately 3% in Cu–Al–Ni alloys to 4% in Cu–Zn–Al alloys. Unfortunately, these copper alloys tend to suffer from low strength and poor corrosion resistance.

NiTi alloys exhibit by far the greatest recoverable strains of commercially available polycrystalline shape memory alloys but generally have a lower range of actuation temperature (approximately in the range −200 to +100°C). Fully recoverable strains of 7% are easily achievable with these alloys and their comparatively high strength and excellent corrosion resistance has resulted in many unique shape memory applications. The poor electrical conductivity of NiTi alloys also allows them to be used in solid-state actuator applications where the alloy is heated by electrical current. Because of this, recent research into smart structures incorporating solid-state actuators has resulted in concurrent development activities on NiTi alloys. The next section will consider NiTi alloys in greater detail.

5.9 Nickel Titanium Shape Memory Alloys

5.9.1 *Background*

Because of its discovery by Buehler *et al.* [35; 36] at the Naval Ordnance Laboratory in California, USA, NiTi alloys are often referred to as *Nitinol* (*NiTi N*aval *O*rdnance *L*aboratory). The shape memory effect is only present in binary NiTi alloys over a very narrow compositional range based around 50 atomic percent, i.e. 50% nickel, 50% titanium. Differences of just 0.1 atomic percent can easily change transformation temperatures by 20°C or more. For this reason production and processing of NiTi alloys must be very strictly controlled. Induction melting is often used to produce the final ingot, ensuring good homogeneity of the alloy, and enabling transformation temperatures to be controlled to within 5°C. Unfortunately this type of careful fabrication and often small production runs adds to the cost of the final product. Because of this NiTi alloys are often regarded as being comparatively expensive.

5.9.2 *Mechanical Behaviour*

The deformation behaviour of NiTi alloys depends heavily on ambient temperature, the phase of the alloy and its transformation temperatures. This is illustrated in Fig. 5.7. The different stages of deformation are labelled from 1 to 4 in each figure.

Figure 5.7(a) represents the behaviour of an alloy in the parent-phase at a temperature above M_d (the temperature above which martensite cannot be stress-induced). The curve exhibits linear deformation (stage 1) up to approximately 0.5% strain (elastic deformation) followed by permanent (plastic) deformation (stage 2). This type of behaviour is typical of conventional metallic alloys.

An alloy tested at a temperature above A_f but below M_d is shown in Fig. 5.7(b). Stage 1 shows some initial elastic loading of the parent-phase. At a particular stress martensite is induced and further strain results in stress-induced martensitic transformation. If the alloy is unloaded at this stage superelastic shape recovery will take place and the curve will follow the path represented by the broken line. However, if the alloy is strained

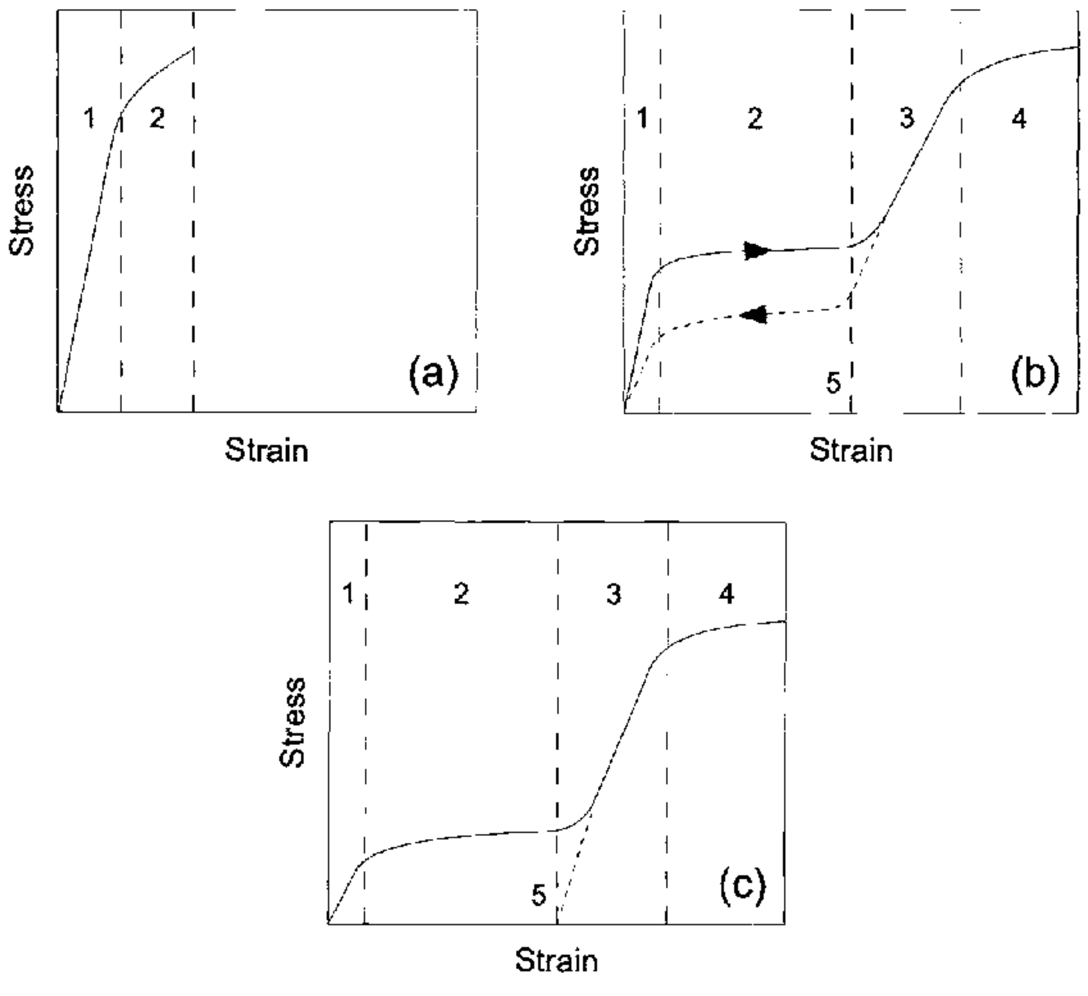

Fig. 5.7 Deformation behaviour of NiTi shape memory alloys at a temperature: (a) above M_d; (b) above A_f but below M_d; (c) below M_f.

further, elastic deformation of the stress-induced martensite (stage 3) will occur until permanent (plastic) deformation sets in (stage 4).

Figure 5.7(c) represents an alloy tested below its M_f temperature in the fully self-accommodated martensite condition. After elastic deformation of the martensite at very low stresses (stage 1), martensite variants begin to realign at a constant stress until reorientation is complete (stage 2). Subsequent loading results in elastic deformation of the martensite variants (stage 3) and eventual permanent plastic deformation (stage 4). If the alloy is unloaded at the end of stage 2 or during stage 3, the material will elastically unload with an apparently permanent strain (5), which can be recovered by heating through the one-way shape memory effect.

All phenomena are observable in a single SMA, depending on the position of ambient temperature with respect to the alloy's transformation temperatures.

5.9.3 *Corrosion Characteristics*

One of the differentiating benefits of NiTi over other commercial shape memory alloys is its excellent corrosion resistance. The passive titanium dioxide (TiO_2) surface film results in a corrosion resistance comparable to 316L stainless steel. Formation of this film is exactly the same as for pure titanium. The film is very stable and resistant to many forms of potentially corrosive attack, however, breaks in the surface can be slow to recover.

NiTi's corrosion resistance has led to extensive studies on the biocompatibility of these alloys and a number of medical applications. It has been established through clinical tests that the bio-compatibility is excellent, with organs showing no signs of metallic contamination. It is thought that the titanium-rich oxide surface prevents potentially harmful nickel reaching tissues. This has resulted in great activity in the medical market which has been one of the catalysts driving recent shape memory research.

5.9.4 *Ternary Additions*

The addition of a third chemical element to NiTi alloys can provide control over particular characteristics of the shape memory effect. For instance:

- Grumman F-14 pipe couplings were made from NiTiFe to provide a very low M_s temperature.

- NiTiCu alloys have become increasingly popular because of their smaller transformation hysteresis and improved cyclic stability.
- The addition of palladium to NiTi presents the interesting possibility of using NiTi-based SMAs in higher temperature applications such as automobiles because of their relatively high transformation temperatures.
- NiTiNb alloys exhibit a wide hysteresis which is particularly useful for coupling devices. This is because it is possible to deform couplings at liquid Nitrogen temperatures (−196°C) and store them in the deformed state at room temperature. Upon subsequent heating the couplings will contract and maintain the clamping pressure when cooled back down to room temperature.

5.9.5 *Summary of Mechanical and Physical Properties*

NiTi alloys offer many unique memory properties. Unfortunately, their comparatively high cost and poor workability is often a factor in determining whether an application has commercial feasibility. For reference and comparison, Tables 5.1 to 5.4 summarise the physical, mechanical and commercial properties of NiTi and copper-based shape memory alloys.

5.10 NiTi Shape Memory Alloys in Smart Applications

Soon after Buehler first discovered the shape memory effect in NiTi alloys the commercial world began to try and assimilate memory characteristics within real products. It is perhaps, because NiTi shape memory effects were first realised in the 1960s that so much initial effort went into finding applications. During this decade, and the one before it, new materials were heralded as the key to economic growth and commercial success throughout many industrial sectors. The impact of thermoplastics, semiconductors and new metallic alloys resulted in this period being referred to as the materials revolution and the discovery of a metal which changes its shape was seen as yet another material that would 'shape' the future of industry. Of course the effect had already been found in copper-based systems but had so far only been viewed as a physical curiosity that could be used to learn more about martensitic transformations.

Table 5.1 Physical properties of shape memory alloys.

	NiTi	Cu-Based Alloys
Density (gcc^{-1})	6.4–6.5	7.1–8.0
Melting point (°C)	1250	950 1050
Thermal conductivity (Wm°C^{-1})		
Martensite	8.6-10.0	-
Parent phase	18	79–120
Electrical resistivity ($\times 10^{-6}\Omega$m)		
Martensite	0.5–0.6	0.14
Parent phase	0.82–1.1	0.07
Co. thermal expansion ($\times 10^{-6}$°C^{-1})		
Martensite	6.6	16.0–18.0
Parent phase	10.0–11.0	-
Specific heat capacity (Jkg°C^{-1})	470–620	390–440
Enthalpy of transformation (Jkg^{-1})	19.0–28.0	7.0–9.0
Transformation temperature range (°C)	-200–-120	-200–$+200$
Corrosion performance	Excellent	Poor
Bio-compatibility	Excellent	Assumed poor

In addition to the discovery of NiTi alloys at the height of a new *materials revolution*, it was also the geographical location of its discovery that resulted in such commercial interest. During the 1960s California was, and arguably still is, the innovation centre of the world. Undoubtedly, NiTi alloys rode the wave of industrial optimism in the 1960s and innovative engineers from many industrial sectors struggled to find applications for it.

However, by 1971, the time that Grumman pipe couplings finally came to market, the strategies for innovation were changing. A new model began to take shape placing more emphasis on the role of the market place. Empirical results based on real innovations began to establish a 'market pull' strategy sometimes referred to as 'need pull' [37]. It began to be realised that the most successful innovations result from either perceived or clearly defined customer needs, resulting in closely focussed research and development. However, shape memory alloy manufacturers continued with a technology 'push' strategy well into the 1980s leaving behind them a trail of failed products such as the thermally activated greenhouse latch [38].

In the early 1980s, at last a genuine market pull began to develop within the shape memory industry. Slowly it became apparent that significant numbers of papers were being presented on medical applications. Shape

Table 5.2 Mechanical properties of shape memory alloys.

	NiTi	Cu-Based Alloys
Young's modulus (GPa)		
Martensite	28–41	70
Parent phase	70–97	70–100
Yield Strength (MPa)		
Martensite	70–140	80–300
Parent phase	195–690	150–350
Ultimate tensile strength (MPa)		
Fully annealed	895	400
Work hardened	1900	1000
Elongation at failure (%)		
Fully annealed	25–50	8–15
Work hardened	5–10	8–15
Hot workability	Poor–fair	Very good
Cold workability	Poor	Good
Machinability	Poor	Very good
Poisson ratio	0.33	-
Wear resistance	Good	-

memory manufacturers and medical device companies who recognised the potential value of this market began to file strategic patents and develop products that provided unique solutions to medical problems. The market pull on shape memory applications gradually intensified during the 1980s until in 1994 the first International Conference on Shape Memory and Superelastic Technologies took place concentrating on practical applications. The influence of the medical market pull was obvious from the number of papers presented on bio-compatibility and medical applications. This conference has now become a regular event and the first European version took place in 1999.

Around the beginning of the 1990s a new market for shape memory alloys also began to emerge, that of "smart materials" and "smart structures". Whilst not being a specific, tangible market segment like that of the medical industry, recent interest in smart technologies has resulted in considerable market pull on shape memory alloy research and development.

Proactive research surrounding smart technologies has produced its own specific journals and conferences and has resulted in a resurgence of interest in using shape memory alloys in actuator applications. For this rea-

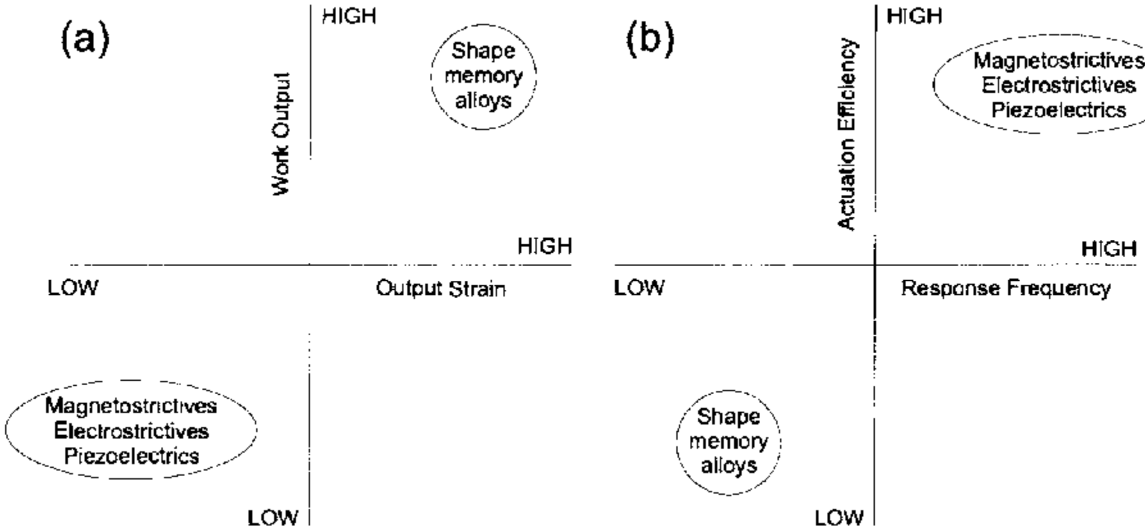

Fig. 5.8 Performance of shape memory alloys: (a) advantages; (b) disadvantages.

son it has become an important strategic segment for shape memory alloy manufacturers and a major driver of current shape memory research and development.

5.11 Shape Memory Alloys as Smart Actuators

It is clear that the main use of shape memory alloys within smart technologies will be as actuators operating through the conversion of thermal energy into motion and work output.

The use of these alloys as solid state actuators offers many benefits [39]:

- High recovery forces.
- Large recoverable output strains.
- Different actuation modes (linear, bending, torsion).
- High work output per unit volume or mass.

It is perhaps the large strains and high work output that offer most opportunities for innovative design with SMAs. The *material function* of the shape memory effect differentiates itself clearly from other actuating materials such as piezoelectrics and magnetostrictives, as shown in Fig. 5.8(a). However, when considering the benefits of SMAs the potential shortcomings should also be considered. Figure 5.8(b) shows how compared to other possible actuators, SMAs suffer from low efficiency (i.e. high loss actuation) and very poor response times or actuation frequencies. Successful applications build on SMA strengths whilst effectively designing out these weaknesses.

The use of NiTi alloys in smart structures is at an embryonic stage. Whilst many researchers are working on applying NiTi to actuator applications in smart structures, fundamental problems for their commercial use remain. These include control paradigms and thermo-mechanical fatigue effects. However, major commercial and academic players continue to research SMAs. If a new high volume application can be found then growth in the SMA "smart sector" will follow.

Much is said about the potential of the smart materials/structures market. For instance, Thompson and Gandhi [40] predict:

> "Smart materials and structures technologies will revolutionise a broad segment of the international market place for products in the defence, aerospace, automotive and commercial-products industries... The total market share of smart materials and structures is projected to exceed $65,000,000 by the year 2010."

Political, economic, social and technological forces will influence this smart materials/structures market and may ultimately dictate whether SMAs prove to be successful in creating innovation and competitive advantage. Thoughts on these key factors are highlighted below [41; 42; 43].

5.11.1 *Political Factors*

Reductions in defence budgets will result generally in less government funded R&D worldwide. This may either have positive or negative effects on SMA research. Although defence-funded R&D is likely to reduce, there is a trend towards increased funding for smart research in general. This has currently renewed interest in SMA technology within the defence market. Government funding for space research will also continue. The trend towards remote vehicle and satellite exploration will provide opportunities for SMA actuators.

5.11.2 *Economic Forces*

Aerospace sales are falling and this in turn exerts economic pressure on aerospace manufacturers. Traditionally these companies have been innovators in many areas of smart research including SMAs. If commercial applications of SMA-based smart structures are not realised soon then funding

Table 5.3 Memory properties of shape memory alloys.

	NiTi	Cu-Based Alloys
Transformation temperature range (°C)	−200–−120	−200–+200
Hysteresis (°C)	20–50	15–20
One-way memory maximum (%)	8	4–6
Two-way memory maximum (%)	3–5	1–4
Superelastic strain maximum (%)	8	2
Work output (Jg^{-1})	1–4	1

of SMA research within these industries is likely to fall sharply over the next 5 to 10 years. The continual push for increased component lifetime and cost reduction may, however, result in a positive drive towards smart technologies which have sensory and adaptive capabilities. It may be that SMAs can find niche applications within these products.

5.11.3 *Social Forces*

Increasingly stringent product safety requirements are likely to exert considerable market pull on sensory and actuator technologies including SMAs. Advances in human control environments are also exerting considerable market pull on these technologies. The trend towards interactive computer interfaces and virtual environments is putting pressure on conventional structural materials to compete with advances in computer hardware and software. Adaptive/smart materials are seen as one way of adding functionality and improving the way we relate to environments and product interfaces. SMAs are one of the few materials already available which satisfy these requirements.

Table 5.4 Economic properties of shape memory alloys.

	NiTi	Cu-Based Alloys
Composition control	Very strict	Fair
Unit cost	High	Fair
Forming cost	High	Fair

5.11.4 *Technological Forces*

Advances in enabling technologies (neural nets, sensors, etc.) will address some of the difficulties associated with the control and implementation of smart structures. In particular, the control of partially transformed SM actuators will become better understood resulting in the possibility of using SMAs as actuators in smart structures. Within the last 5 years there have also been considerable advances in NiTi product geometries such as thin films and tubing. These 'new' product forms will lead to greater freedom when designing adaptive structures and actuators and which will lead to further SMA applications.

5.12 Shape Memory Alloys and their Fit to Smart Technologies

It is beyond the scope of this chapter to argue deeply about the definition of what constitutes a smart material or structure. However, the following definition based on reports resulting from the UK Department of Trade and Industry's Overseas Science and Technology Expert Mission to Japan, does summarise the important issues concerning the nature of the field and the materials that can be included within it:

Smart Materials Materials with inherent functionality designed at a molecular level.

Smart Structures Systems with added functionality imparted by the integration of physical elements such as sensors and actuators with non-active materials.

It is possible to see how shape memory alloys fall into both categories. The smart material defined above requires design at a molecular level such that structural integrity, sensor and actuator functions are combined at a microscopic level to form a monolithic material rather than the macroscopic level where monolithic elements are combined to form a smart structure.

5.12.1 *Shape Memory Alloys — A Smart Material?*

The concept of smart materials and their design at a molecular level is usually interpreted as the manipulation and integration of discrete molecules, each one of which has either: a sensor, actuator or structural function. In this respect a smart material is actually a smart structure on a microscopic level. In shape memory Alloys these three functions are combined at an atomic level. In this respect the ability of shape memory alloys to respond autonomously to external stimuli is inherent and therefore fulfils one of the most important requirements of a smart material; although with relatively limited range of functionality.

In addition, a smart material should be able to respond in a controllable manner that is pre-programmed during its manufacture and processing. Again this is easily achievable with SMAs. Careful control of the alloy content and subsequent processing can be used to 'fine tune' the transformation temperatures (sensor function), the force and degree of shape recovery (actuator function) and the strength of the alloy (structural function).

Another requirement of smart materials is that actuation should only occur where it is needed. Actuators dispersed at a molecular level within a monolithic structure would on the face of it seem very difficult. However, a new method of setting the memory into discrete areas using a laser means that monolithic shape memory devices can now be made with actuators dispersed within an otherwise entirely structural matrix. A microgripper using this technique has been commercially produced and may in this respect be one of the first truly "smart material" applications of SMAs [44].

5.12.2 *Shape Memory Alloys in Smart Structures*

Essentially, two approaches have been adopted in the use of SMAs within smart structures. The first is to use SMA actuators in a relatively conventional form to drive the structure of interest. This is essentially an extension of conventional mechatronics, with complex actuation systems replaced by shape memory alloys. However, such applications differ from more conventional SMA applications since actuators are driven electrically, allowing integration of the actuation system with the control and sensing parts of the smart structure. Within this family of applications are those classed simply as "smart mechanisms". Examples include variable geometry aerofoils/hydrofoils which have been developed as demonstrators by a number of centres [45]. In these "mechanisms" SMA actuators are used to vary the geometry of 'flexible' structures in a manner analogous to human muscles, by using the varying strain available from an SM actuator as it is heated proportionately through its transformation/reversion ranges, and the mechanics of actuation are relatively conventional and simple.

At the other extreme of 'conventional' actuation is the use of SMAs in more complex structural systems. Such an example is the development of active struts for truss structures. Lightweight space truss-structures require active control to eliminate vibration and resonance. The incorporation of active struts, which can excite a structure with a cyclically imposed strain, can produce damping. A major problem is usually low frequency vibration, and low-bandwidth high-strain actuators are optimal for such active trusses. SMAs fulfil this requirement and designs have been developed for trusses based on SMAs [46]. These are relatively conventional in the sense that they use the SMA in a partially constrained actuation mode, similar to many conventional thermal sensor applications, but with the active trusses driven electrically.

A second approach to SMA-based smart structures is a more radical departure from conventional applications. This is to use SMAs as distributed strain actuators either embedded within or surface mounted to structures. This is currently the most widely investigated area since SMA wire actuators integrate well with advanced composite materials. The use of embedded SMA actuators has been demonstrated for vibration and shape control of composite components, and preliminary work has shown the potential of such actuators for damage control.

5.12.2.1 *Passive Composite Structures*

These rely on the inherent damping capacity of SMA alloys in the martensitic phase and do not involve any macroscopic shape change or motion from the 'actuator'. An example of this is the alpine ski developed at EPFL in Lausanne, Switzerland, where CuZnAl SMA alloys are integrated within a modified ski to damp vibration [47]. The damping mechanism relies on very small movements between martensite variants within the SMA to absorb vibrational energy through the hysteresis associated with reversible mechanical reorientation of a martensitic material. As the ambient temperature of the skiing conditions falls and the snow surface becomes harder, the martensitic transformation increases the damping capacity of the ski. A similar strategy is also employed for the damping of seismic vibrations in building structures using superelastic NiTi alloys [48].

Unfortunately passive control is limited to specific operating conditions. There is therefore more interest in the *active control* of smart structures as this can result in a much greater operational envelope.

5.12.2.2 *Structural Shape Control*

Many workers have demonstrated structural shape control by incorporating SMA actuators away from the neutral axes of composite components; bending introduced by actuators controlling the component's 'shape'. If actuators are placed either side of the neutral axis they can also work against one-another to provide sensitive control of shape deformation. Two additional forms of shape control have also been demonstrated which do not per se depend on the macroscopic strains of distributed actuators. These have been termed active property tuning (APT) and active strain energy tuning (ASET).

APT involves no shape change in an actuator but instead depends on its stiffness change when heated through the transformation range; transformation from martensite to parent-phase increasing the effective stiffness of a SMA by more than 200%.

Such changes can influence the stiffness of the host composite materials resulting in control of their deflection under imposed loads. For example, modelling has shown that in quasi-isotropic carbon fibre reinforced plastics (CFRP), the deflection of clamped simply supported plates can be reduced by 6% using APT; although the volume fraction of SMA required is high ($\sim$ 50%). The actuator must however be oriented correctly to maximise this effect.

During ASET an actuation strain is induced in the composite, however, no macroscopic shape change occurs since actuators are distributed throughout the host composite. This introduces internal stress into the hybrid material. Models exploring this effect have shown that the deflections of loaded simply supported plates can be reduced, and that a smaller volume fraction of actuator is required compared to APT, to produce control over deflection. For example, in quasi-isotropic CFRP laminates $\sim$ 80% reductions in deflection can be achieved with only 10 vol% actuator. The reduction of deflection also depends on the recovery force of the actuator (i.e. the amount of memory strain).

A good example of active shape control is the work carried out at Cranfield University, shown in Fig. 5.9. Here it is used to change the 'angle of attack' of a glass reinforced plastic wing structure. By embedding just two SMA wires at the root of a composite wing, (at an angle of 45° to the major axis of the aerofoil), its angle of attack can be actively controlled in real-time.

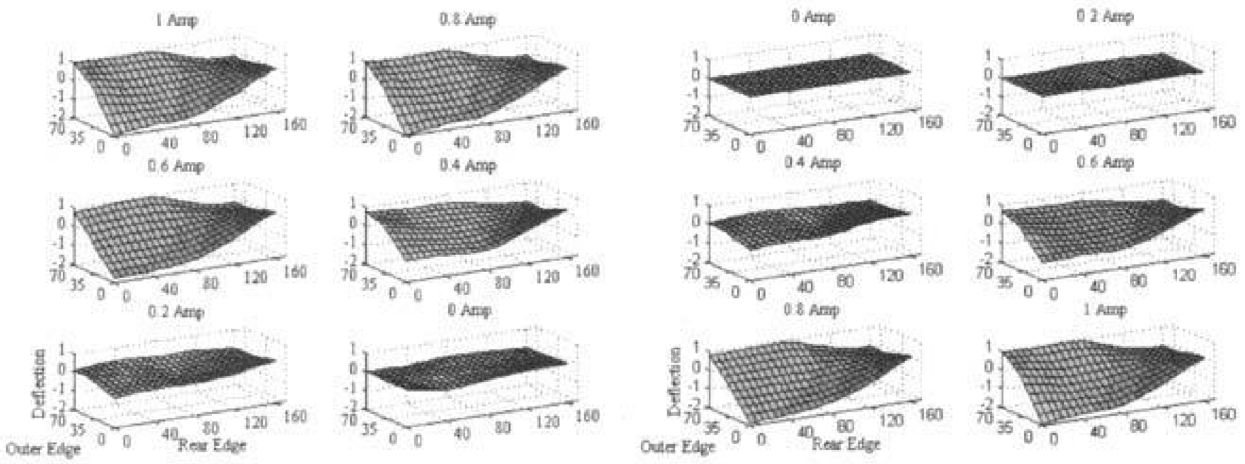

Fig. 5.9 Active shape control of a model adaptive wing.

These examples illustrate the effects of not only varying level of actuation within individual SMA actuators, but also the possibility of activating actuators at different positions within the composites and in different volume fractions, to produce widely variable actuation/shape responses.

5.12.2.3 *Vibration Control*

The second major area of interest in the application of SMA smart composites is in vibration control. In smart materials vibration control has been a major area of investigation with particular emphasis on the use of piezoelectric materials as high band-width, low-strain actuators. However, there are applications where lower band-width high strain-output actuators are required (e.g. for low frequency vibration control) and it is in this area that one strategy employing SMAs has been developed. Vibration control in smart structures has traditionally involved the sensing of vibration (or strain) within a structure, and the imposition of 'anti-strain' through a closed loop control system. Such a use of SMAs essentially involves the design of a suitable actuator and its control strategy, and work is well developed in a number of applications. However, there are other possible uses of SMAs, most again associated with their use in advanced composites.

Conventional closed-loop feedback systems between strain sensors and actuators can be used to create smart structural systems, but in no way create truly adaptive materials. However, the incorporation of SMAs into composite materials can produce such a functional composite. For example, one whose resonance frequencies can be varied by means of an external control variable. The approach here is not to strain-follow (to produce vibration cancellation), as in the case of piezoelectric actuators, but to modify composite properties such that resonance frequencies are actively moved away from excitations present within a structure. It has already been shown that effective bending stiffness can be modified by both APT and ASET, and both approaches can also be used to control resonance frequencies. APT can significantly modify the lower resonance modes of isotropic CFRP plates; shifts of resonance to higher frequencies depending on both the degree of activation (i.e. the effective stiffness change), the orientation of the actuators, and volume fraction of actuator. SMA composites controlled by APT not only result in shifts in resonance frequency, but can also control mode shapes.

It will also be of no surprise that ASET can also control resonance frequencies and mode-shapes. Doublings of the first natural frequency have been reported using only 10 vol% SMA actuator incorporated in quasi-isotropic CFRP laminates and ASET also directly modifies mode shapes.

5.12.2.4 *Buckling Control*

APT and ASET introduce in-plane loads into composite structures which not only modify their apparent flexural stiffness and modal responses, but also alter buckling characteristics. For example, APT has been shown [49] to increase buckling loads as a result of the NiTi's higher Young's Modulus in the parent-phase. Modelling of ASET has also shown a wide range of control options which depend on the orientation of the embedded actuators (compared to that of the applied load).

In the case of buckling, some components more typical of aerospace structures have also been considered. Finite element analyses of buckling blade and T-stiffened panels have been carried out with and without NiTi actuators providing control. Improved buckling [50] loads have been predicted for 1st to 5th buckling modes, and show that at high actuation strains, up to a 12% increase in load can be achieved for T-stiffened panels and ~ 4% for the blade stiffened. If multiple actuators are placed in a blade stiffened panel, increases in buckling load can also be raised further.

5.12.2.5 *Acoustic Radiation*

In addition to the control of shape, vibration and buckling, APT and ASET, have also shown potential for the control of acoustic transmission and radiation efficiency [49; 43]. Acoustically excited SMA reinforced composites can adaptively change radiation efficiency, transmission loss and directivity patterns for transmitted sound. The main processes exploited in such control have been to shift minima in transmission loss spectra, as well as changing the radiation efficiencies associated with mode shapes. The latter provides much promise for the control of sound radiation over a broad band of frequencies and the former the possibility of 'tuning' acoustic panels.

5.12.2.6 *Active Damage Control*

The final area of current interest is the use of SMA actuators for active damage control. This uses embedded sensors to detect the presence of cracks or other damage within a structure and SMA actuators to prevent propagation or damage becoming critical. Two main approaches have been investigated. In the first prememorised SMA wires embedded within composite materials are activated by heating. They attempt to return to their memorised length and result in a change in the internal stress–strain distribution. This approach has been analysed [52; 53] and shows that the recovery force under these conditions acts as a concentrated force at the free edge of the SMA hybrid composites. Because of the low internal stresses generated, this approach is not very effective [54] in influencing the stress-intensity at a crack-tip unless the SMA actuator bridges a crack. In such circumstances the crack surface then becomes a free surface, and the actuator imparts a normal stress at the tip leading to closure and a reduction in stress-intensity.

In a second concept, SMA wires with no memory are embedded into a composite component. When a crack propagates and is close to or passes through the embedded SMA actuators its stress-field results in a large strain in the SMA actuators. This effectively primes the one-way memory effect around the crack-tip. When these actuators are subsequently activated, a recovery stress is generated only in the vicinity of the crack-tip, causing reduction in stress-intensity. This approach relies on the deformation of the matrix around the actuators since deformation is required to induce the one-way effect. It has therefore been speculated [55] that this mechanism will be much more appropriate for higher strain thermoplastic, rather than brittle thermoset polymer matrices.

5.13 Final Thoughts

This chapter has examined some of the issues associated with the fit of shape memory alloys within smart technologies. The differentiating benefits of certain shape memory properties offer real opportunities for innovation. If this potential is ever going to be realised however, consideration should be given to how these market opportunities can best be exploited.

Both reactive market opportunities and proactive technological opportunities need to be present for successful innovation through shape memory alloys. It is interesting that the two markets exerting a pull on shape memory alloys are essentially concerned with utilising different memory effects. That is, the major applications and patents within the medical sector are concerned with superelasticity, whilst the smart structures researcher's concern is that of repeatable shape change in actuator applications.

Medical device manufacturers and smart structures researchers are requiring higher performance and more functional materials and devices. Developments in these areas are already exerting a pull on shape memory alloy development and this is likely to intensify as the need for smart technologies increases.

Bibliography

[1] Perkins, J. (1974) *Mat. Sci. & Eng.*, **51**, 182.
[2] Schroeder, T. A. and Wayman, C. M. (1977) *Scr. Metal.*, **11**, 225.
[3] Saburi, T. and Nenno, S. (1974) *Scripta Met.*, **8**, 1363.
[4] Oshima, R. and Naya, E. (1975) *J. Japan. Inst. Met.*, **39**, 175.
[5] Takezawa, T. and Sato, S. (1976) *Proc. 1st JIM Int. Symp. on New Aspects of Martensitic Transformations*, pp. 233.
[6] Zhu and Yang (1988) *Scripta Met.*, **22**, 5.
[7] Ölander, A. (1932) *Z. Krystall*, **83A**, 145.
[8] Greninger, A. B. and Mooradian, V. G. (1938) *Trans. AIME*, **128**, 337.
[9] Chang, L. C. and Read, T. A. (1951) *Trans. AIME*, **189**, 47.
[10] Buehler, W. J. and Wiley, R. C. (1965) US Patent 3 174 851.
[11] Duerig, T. W. (1990) *Engineering Aspects of Shape Memory Alloys*, Butterworth–Heinemann.
[12] Wever, D. J., Veldhuizen, A. G., Sanders, M. M., Schakenraad, J. M. and van Horn, J. R. (1997) *Biomat.*, **18**, 1115.
[13] Dutta, R. S., Madangopal, K., Gadiyar, H. S. and Banerjee S. (1993) *Brit. Corr. J.*, **28**, 217.
[14] Ryhanen, J. (1999) PhD thesis, Department of Surgery, Oulu University, Finland.
[15] Fernald, R., Fritz, D., Sievert, C. and Stice, J. (1994) *Proc. 1st Int. Conf. on Shape Memory and Superelastic Technologies, Pacific Grove, California*, pp. 341.
[16] Finander, B. V. and Liu, Y. (1994) *Proc. 1st Int. Conf. on Shape Memory and Superelastic Technologies, Pacific Grove, California*, pp. 151.
[17] Andraesen, G. F. (1980) *Am. J. Orthod.*, **78**, 528.
[18] Shape Memory Applications Inc., USA, (1996) *Shape Your Future with...*, product brochure.
[19] Duerig, T., Pelton, A. and Stockel, D. (1999) *Mat. Sci. & Eng. A*, **273–275**, 149.

[20] Cwikiel, W., Stridbeck, H. and Trandberg, K. G. (1993) *Radiology*, **187**, 661.

[21] Furukawa Electric Co. Ltd., Japan, product brochure.

[22] Molloy, K. (1995) *The Mail on Sunday*, 28th May 1995, pp. 42.

[23] Thomas Bolton Ltd., UK, *SMA The Metal With a Mind*, product brochure.

[24] Kapgan, M. and Melton, K. N. (1990) *Engineering Aspects of Shape Memory Alloys*, Butterworth–Heinemann.

[25] Raychem, USA, *Unilok™ Rings*, product brochure.

[26] Harrison, J. D. and Hodgson, D. E. (1975) *Shape Memory Effects in Alloys* (ed. J. Perkins), Plenum Press, pp. 517.

[27] Michael, A. D. (1994) *Proc. 1st Int. Conf. on Shape Memory and Superelastic Technologies, Pacific Grove, California*, pp. 283.

[28] van Moorlegham, W. and Otte (1990) *Engineering Aspects of Shape Memory Alloys*, Butterworth–Heinemann.

[29] Kao, M., Schmitz, D., Thoma, P., Klaus, M. and Angst, D. (1996) *Proc. 5th Int. Conf. on New Actuators — Actuator 96, Bremen, Germany*, pp. 124.

[30] Hashimoto, M., Takeda, M., Sagawa, H., Chiba, I. and Sato, K. (1985) *J. Robotic Sys.*, **2**, 3.

[31] Guénin, G. and Gaudez, P. (1996) *Proc. 3rd Euro. Conf. on Smart Structures and Materials and Int. Conf. on Intelligent Materials, Lyon, France*, pp. 493.

[32] Benzaoui, H., Lexcellent, C., Chaillet, N., Lang, B. and Bourjault, A. (1997) *J. Intell. Mat. Sys. & Struct.*, **8**, 619.

[33] Tamura, H., Suzuki, Y. and Todoroki, T. (1986) *Proc. Int. Conf. on Martensitic Transformations, Nara, Japan*, pp. 736.

[34] Melton, K. N. and Harrison, J. D. (1994) *Proc. 1st Int. Conf. on Shape Memory and Superelastic Technologies, Pacific Grove, California*, pp. 187.

[35] Buehler, W. J., Gilfrich, J. W. and Wiley, R. C. (1963) *J. Appl. Phys.*, **34**, 1475.

[36] Buehler, W. J. and Wiley, R. C. (1965) US Patent 3 174 851.

[37] Myers, S. and Marquis, D. G. (1969) *Successful Industrial Innovation*, National Science Foundation.

[38] Beta Metals, company brochure.

[39] Stoeckel, D. (1990) *Adv. Mat. & Processes*, Oct. 1990, 33.

[40] Thompson, B. S. and Gandhi, M. V. (1990) *Smart Materials and Structure Technologies: The Impending Revolution*, Technomic.

[41] Chamberlain, G. (1995) *Design News*, **50**, 70.

[42] Sheehan, T. (1995) *The Architects Journal*, **202**, 37.

[43] Rogers, C. A. (1995) *Scientific American*, Sep. 1995, 122.

[44] Bellouard, Y., Lehnert, T., Bidaux, J. E., Sidler, T., Clavel, R. and Gotthardt, R. (1999) *Mat. Sci. & Eng. A*, **273–275**, 795.

[45] Wield, D. N. and Gillam, E. (1972) *Scripta Met.*, **6**, 1157.

[46] Maclean, B. J., Draper, J. L. and Misra, M. S. (1991) *Proc. 1st Joint US–Japan Conf. on Adaptive Structures, Hawaii*, pp. 1038.

[47] Gotthardt, R., Scherrer, P. and Stalmans, R. (1999) *Proc. Int. Symp. on Shape-Memory Materials, Kanazawa, Japan*, pp. 475.

[48] Casciati, F., Faravelli, L., and Petrini L. (1998) *Proc. 4th Euro. Conf. on Smart Structures and Materials and 2nd Int. Conf. on Micromechanics, Intelligent Materials and Robotics, Harrogate, UK*, pp. 321.

[49] Liang, C., Jia, J. and Rogers, C. (1989) *Proc. 30th AIAA/ASME/ASCE/AHS/ASC Structures, Structural Dynamics and Materials Conf.*, pp. 1504.

[50] Thompson, D. H. and Griffin, O. H. (1992) *Proc. Conf. Recent Advances in Adaptive and Sensory Materials and their Applications, Blacksburg, Virginia*, pp. 377.

[51] Rogers, C. A., Fuller, C. R. and Liang, C. J. (1990) *J. Sound & Vib.*, **136**, 164.

[52] Dasgupta, A., Wan, Y. and Sirkis, J. S. (1992) *Smart Mat. & Struct.*, **1**, 101.

[53] Rogers, C. A., personal communication.

[54] Jensen, D. W., Pascaul, J. and August, J. A. (1992) *Smart Mat. & Struct.*, **1**, 31.