Shape Memory Alloys
An Introduction

Seminar Report

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By

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Abstract

Shape memory alloys are functional materials which offer attractive potentials such as reversible strains of several percentage, generation of high recovery stresses, high power-to-weight ratio, high damping and high fatigue life. This seminar gives an introduction to the origin, mechanism and characteristics of the unique phenomena of shape memory effect and superelastic effects. Different properties and characterisation techniques are also discussed. Various applications in the fields of engineering and bio-medicine are briefly discussed.

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Chapter 1

Introduction

It goes without saying that the development of new materials is of central importance in every technological advancement. Our expectation of higher functionality along with higher reliability from our technology has made the use of advanced materials inevitable. The current trend is to replace conventional materials by what may be called 'functional materials'. Shape memory alloys are functional materials exhibiting many unique properties. By exploitation of these unique properties it is possible to design systems that are more compact, more automatic and possess previously unthinkable capabilities.

With the increase in the complexity of the physical systems, there is a need to incorporate biological capabilities like self adaptability, self sensing, memory and feedback into the systems. This is the basic philosophy of the rapidly emerging field of 'smart structures'. The contribution of shape memory alloys to smart structures is mainly as actuator material. They can be used to apply force, change shape and stiffness and do mechanical work on demand. The evolution of the smart concept has lead to a manifold increase in the importance of shape memory alloys .

1.1 Basic Concepts

The term Shape Memory Alloys (SMAs) is applied to a group of metallic materials that when subjected to appropriate thermal procedure demonstrate the ability to return to some 'previously remembered shape'. This means that it is possible to imprint some shape in the memory of these materials. If the material is physically deformed, it is capable of returning to its original shape prior to deformation upon the application of an appropriate thermal cycle.

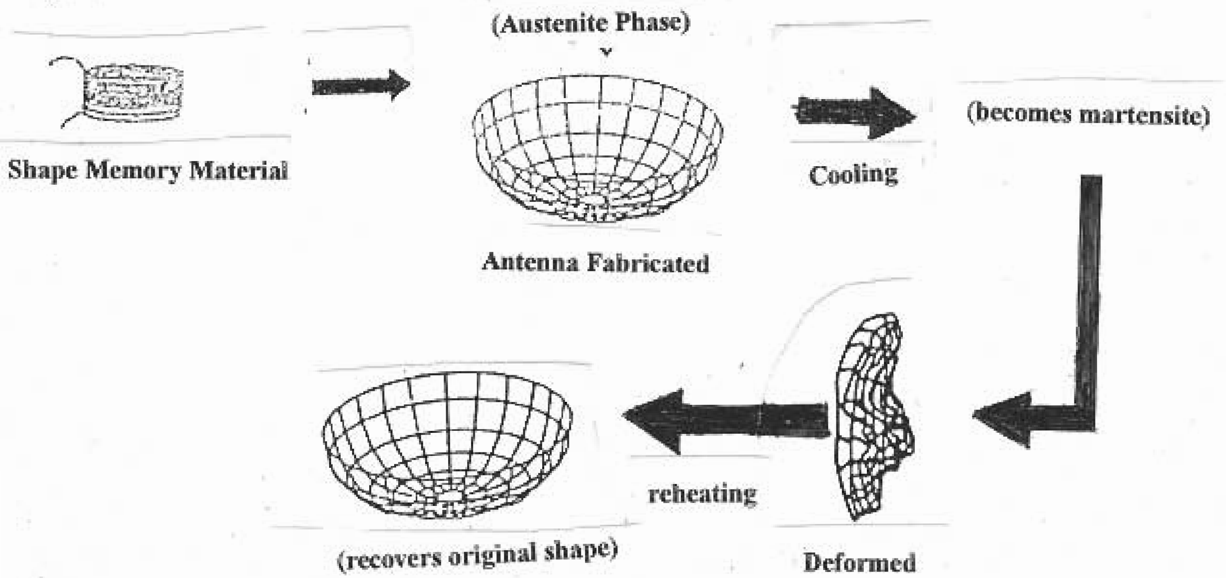


Figure 1.1: A shape memory antenna for space applications

This ability of 'memorising' a particular external shape is a direct consequence of a thermodynamically reversible transformation of the alloy's crystal structure. In general, there are two crystal structures or phases associated with a shape memory alloy. The phase corresponding to higher temperature is called the 'austenite phase' and the one corresponding to lower temperature is called the 'martensite phase'. There is an alloy-specific critical temperature at which the transformation takes place. On sudden cooling (quenching) below this critical temperature the material changes its phase from austenite to martensite. In the martensite phase, the alloy is highly plastic and can be easily be manipulated through very large strain range with relatively little change in material stress. When heated above the critical temperature again the phase changes to austenite. Here the alloy resumes the shape that it initially had before deformation. (See fig.1.1).

In the austenite phase SMAs have high strength, high modulus and behaves much like a normal metal. So in shape memory alloys, changes in temperature can be used to obtain change in shape, stiffness, position, natural frequency and other mechanical properties. In addition to the temperature induced shape memory effect, SMAs also show 'superelastic effect'. This means that if the material is kept at constant temperature in the austenite phase and mechanically loaded, it shows capability of recovering large strains. The yield strain in superelastic effect is nearly 30 times that of normal steel.

1.2 Materials showing shape memory

A wide variety of alloys are known to exhibit shape memory. Only those that can give substantial strain recovery, can generate large enough force when constrained and have high power to weight ratio are of commercial interest. The most common class of shape memory alloys is Nitinol (Ni-Ti alloys). Other alloys showing this effect include CuZn, NiAl, NiMn, CuZnAl, CuZnSi, CuZnGa, NiMnAl, NiMnCr, NiMnTi, NiTiFe, MnFeSi, AuCd and InTl [5],[8],[11], [19]. Table 1.1 shows details of some commercially available SMAs. M_s denotes the temperature at which the martensitic transformation starts, at. and wt. denote atomic and weight percentage respectively.

Table 1.1: Data for some commercially available Shape Memory Alloys

Alloy	Composition	$M_s(^oC)$	Temperature Hysteresis (^oC)	Volume change
AgCd	44 to 49at.%Cd	-190 to -50	around 15	-0.16
AuCd	46.5 to 50at.%Cd	30 to 100	around 15	-0.41
CuAlNi	14 to 14.5wt.%Al 3 to 4.5wt.%Ni	-140 to 100	around 35	-0.30
CuAuZn	23 to 28at.%Au 45 to 47at.%Zn	-190 to 40	around 6	-0.25
CuSn	around 15at.%Sn	-120 to 30	around 10	-0.5
CuZn	38.5 to 41.5wt.%Zn	-180 to -10	around 10	-0.5
InTL	18 to 23at.%Tl	60 to 100	around 4	-0.2
NiAl	36 to 38at.%Al	-180 to 100	around 10	-0.42
TiNi	49 to 51at.%Ni	-50 to 100	around 30	-0.34
FePt	around 25at.%Pt	around -130	around 4	0.8 to -0.5
MnCu	5 to 35at.%Cu	-250 to 180	around 25	0.8 to -0.5

Source: Ref. [5]

Beside these metallic alloys, certain other substances have been observed to display shape memory behaviour. Prominent among these are ceramics such as Y-Ba-Cu-O, Ti-Ba-Ca-

Cu-O and Bi(Pb)Sr-Ca-Cu-O. Plastics like Norsorex and Zeon Shable also exhibit this effect [10].

1.3 History of Shape Memory Alloys

The earliest recorded observation of the shape memory effect was by Chang and Read in 1932. They noted the reversible change in the crystal structure of AuCd. Later in 1951, the shape memory effect was observed and investigated in detail in bent AuCd bars. However the real breakthrough came in 1962 when the effect was found in equiatomic NiTi. Nickel Titanium alloys of various compositions were prepared and tested. William J. Buehler of the Naval ordinance laboratory, Maryland, U.S. was the one to discover this class of SMAs. A generic name of this group of alloys was coined as Nitinol. Nitinol stands for Nickel Titanium Naval Ordinance Laboratory. In 1980, it was used by NASA in an Earth orbiting space station. Within the last ten years, a number of commercial products have appeared in the market and the understanding of the phenomenon has very much increased. The unique properties of shape memory alloys have made them an important and often single choice as functional materials.

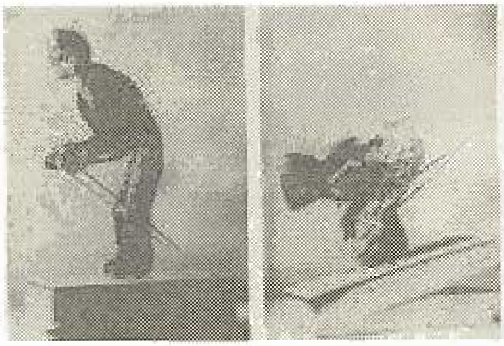


Figure 1.2: Art piece "The Skier" Designed for Winter Olympics, 1990 Source: Ref. [20]

Layout of the Seminar: In chapter 2 we explain the mechanism of martensitic transformation and the shape memory effect as its consequence. In chapter 3, the phenomena of isothermal superelasticity (psuedoelasticity) is investigated. Also, various physical properties shown by some common shape memory materials are discussed. In chapter 4, an attempt is made to classify various applications of the SMAs with brief descriptions of various examples.

Chapter 2

The Shape Memory Effect: Mechanism and Characteristics

As mentioned earlier, the shape memory effect is basically a result of crystal transformations. In this chapter, we shall study these transformations in some detail. We shall also look into the shape memory effect and its various aspects more precisely.

2.1 Martensitic Transformations

As mentioned, a shape memory alloy exists in one of the two stable phases corresponding to two different, alloy specific temperature ranges. The phase which is stable at higher temperature is called the austenite phase and other is called the martensite phase. In general, when the material in austenite phase is quenched, it gets hardened. After polishing and surface treatment, observations with a microscope show extremely fine structure. This is the martensite phase. The martensitic transformations involve shearing deformation resulting in cooperative diffusionless atomic movement. This means that the atoms in the austenite phase are not shifted independently but undergo shearing deformation as a single unit while maintaining relative neighborhood. A one-to-one lattice correspondence is maintained between the atoms in the parent phase and the transformed phase. Since the transformation is diffusionless, the concentration of solute atoms dissolved in the martensite phase is equal to that in the parent phase.

2.1.1 Characteristic temperatures

The reversible phase transformation depends on four different temperatures namely :

$(i)A_s$ (Austenite start)

$(ii)A_f$ (Austenite finish)

$(iii)M_s$ (Martensite start)

$(iv)M_f$ (Martensite finish)

Note that $M_f < M_s < A_s < A_f$

A_s and A_f define the range of transformation from martensite to austenite on heating. M_s and M_f define the inverse transformation range on cooling.

2.1.2 Transformation Kinetics

Martensitic transformations can either be temperature induced or stress induced. Stress induced transformation occurs at constant temperatures moderately above A_f. This results in what is called 'superelasticity' and is discussed in chapter 3. In this chapter we shall discuss temperature induced transformations only. When the temperature falls below M_s, the transformation initiates and proceeds by nucleating new crystals. This occurs at about one-third the speed of elastic waves in solids [5]. In some cases, even if the temperature is above M_s or kept at constant value below M_s, the transformation commences after some alloy-specific incubation period [8].

2.1.3 Thermoelastic transformations

Temperature induced martensitic transformations are categorised into two classes: thermoelastic and non-thermoelastic. In non-thermoelastic martensitic transformations, the martensite crystal grows by nucleation to its final size almost instantly and after that does not grow or shrink with temperature changes. On the other hand in thermoelastic transformation, even after the crystal has nucleated and reached equilibrium, the crystal grows or shrinks with temperature changes. (see fig. 2.1) The rate of growth or shrinkage is proportional to the applied cooling or heating rates respectively. The crystals that are first transformed at

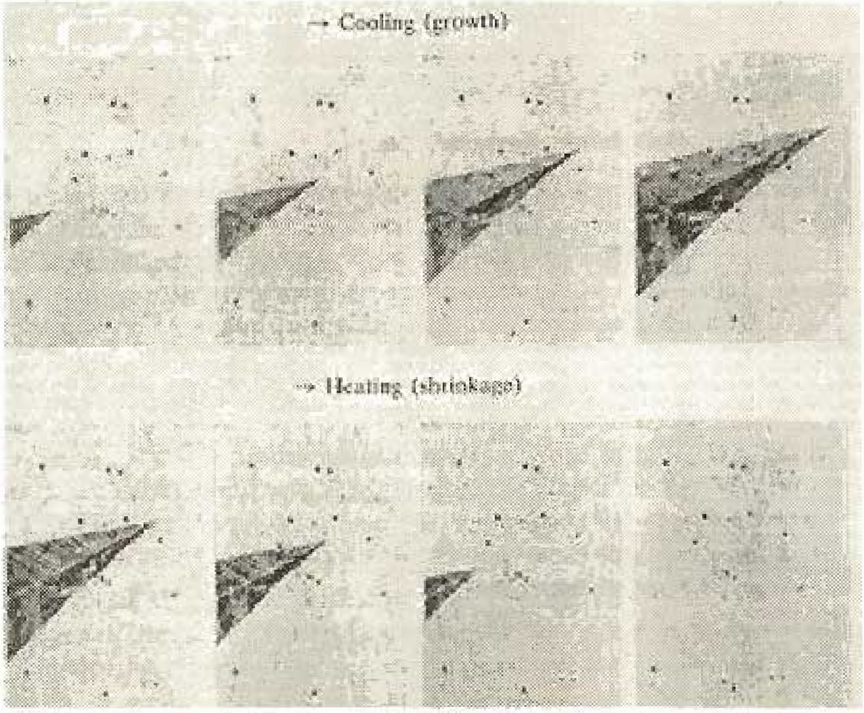


Figure 2.1: Growth and Shrinkage of Thermoelastic Martensitic Crystal due to Cooling and Heating in CuAlNi. Source: Ref. [5]

temperature M_s are the last to undergo reverse transformation at A_f. Therefore, thermoelastic martensitic transformations are reversible in nature and are crucial for shape memory effect to occur.

It is observed that the reverse cycle does not follow the same path as the forward cycle. Therefore a hysteresis exists in the properties in the thermal cycle (see fig. 2.2). The extent of hysteresis is measured by 'hysteresis temperature' defined as $(A_s - M_s)$. Hysteresis temperature is highly alloy specific. In general, it is high for non-thermoelastic transformations and relatively very low for thermoelastic transformations. For Au47.5at.%Cd it is 15^o while for Fe30at.%Ni it is about 400^o [9]. This once again gives the indication that only thermoelastic transformations can be responsible for a highly reversible phenomena of shape memory.

In martensite transformations of shape memory alloys, the shear deformation involves very small volume change (see table 1.1). Consequently, the transformation proceeds without inducing any plastic deformation of the surrounding parent phase. It is for this reason that

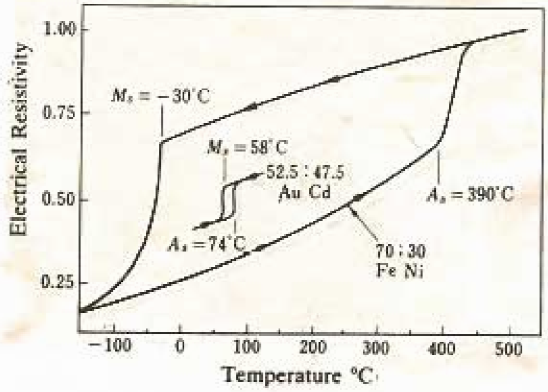


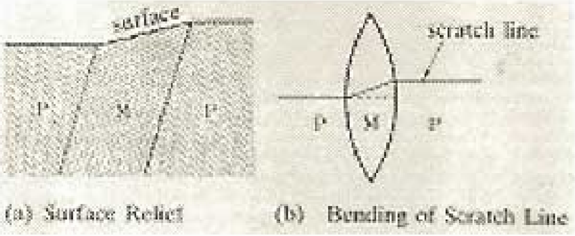
Figure 2.2: Comparison of Hysteresis in Electrical Resistivity accompanying Non-Thermoelastic (FeNi) and Thermoelastic (AuCd) martensitic transformations. Source: Ref. [5]

the transformations are thermoelastic in nature. On the other hand, since the volume change accompanying transformation of ferrous alloys and steels are large, it is non thermoelastic and therefore does not induce shape memory effect.

Also, for shape memory effect to occur, the transformation energy and the energy needed for plastic deformation must be negligible small. Except for some ferrous based SMAs, all SMAs essentially undergo thermoelastic martensitic transformation [5].

2.1.4 Martensitic transformations and shape change

The martensitic transformations are accompanied by shape changes (or surface relief) of a definite value. This shape deformation accompanying the transformation is manifested directly as change in external shape of the specimen. If a scratch line is constructed on the surface in the parent shape, bends will arise in the line at the places where transformation has taken place. As mentioned earlier, the transformation mechanism involves shear defor-



(a) Surface Relief (b) Bending of Scratch Line

Figure 2.3: Formation of Surface Relief and Bending of Scratch Mark Accompanying Martensitic Transformation. Source: Ref. [5]

mation. The plane along which this shear occurs is called 'habit plane'. In general, upon transformation, a single crystal in the parent phase results in a number of martensites with different habit plane orientations. These martensites with different habit plane orientations are called 'variants' and are scattered throughout the specimen. In general, there are 24 martensitic variants created within one parent phase lattice(see section 2.2.1). These variants form and arrange themselves such that the transformation strain is minimised. This property is called 'self accommodation'. In absence of any external force, even if the transformation results in shape deformation of individual variants, the specimen as a whole does not experience any change in shape. This is a direct consequence of the self accommodation property. This plays an important role in deformation-and-restoration mechanism of shape memory alloys and is discussed in next section.

2.2 Shape Memory Effect : Mechanism

Let us look at the shape memory effect more precisely. The stress-strain curves of CuZnSn is shown in figure 2.4. It may be noted that this is highly dependent on the characteristic temperatures (i.e M_s, M_f, A_s and A_f). When $T < A_f$, the material is plastic. The strain in the specimen will not recover fully even if the stress the is removed. The plasticity increases with further decrease in temperature. However, this residual strain can be removed by heating the sample above A_f. This is shown by dotted lines. This phenomena is nothing but the shape memory effect.

2.2.1 Origin of Shape Memory Effect

We have mentioned that the martensitic transformation in a crystal involves shear deformations along habit planes. In general, there can be six habit planes with shear force acting in four directions in each habit plane. For example, in y-z habit plane shear force can act along +y, -y, +z and -z. Therefore there can be 24 different variants of the transformed crystal structure. The pair of variants arising from shear force in opposite directions are called 'correspondence variants'. The recoverable strains in the shape memory effect are basically the strains associated with conversions between these variants. When an external force is

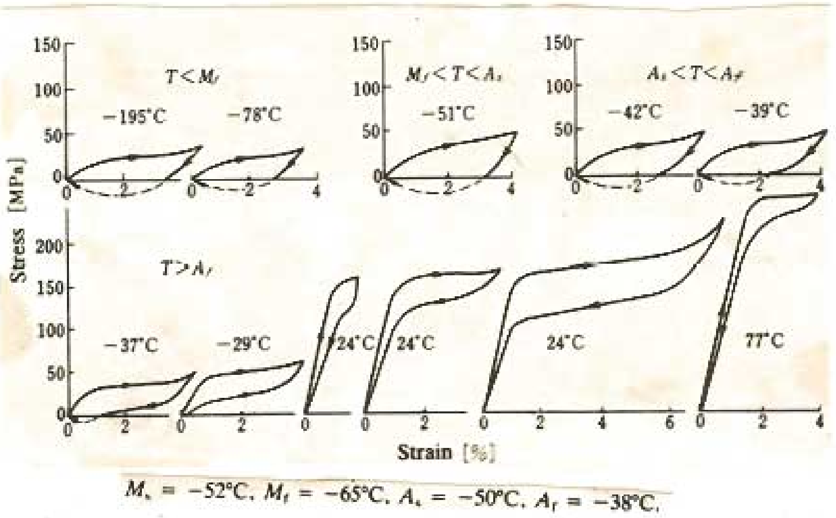


Figure 2.4: Stress-Strain Curve of Cu34.7Zn3.0Sn(wt.%) at various temperatures.
Source: Ref. [5]

applied with $T < M_f$, 24 different variants merge and a variant of a certain orientation begin to grow. This conversion between the variants occurs via twinning deformation. This twinning deformation then results in change of the external shape of the SMA specimen. The conversion first starts within the correspondence variants pair and subsequently among different pairs until finally the entire specimen consists of a single variant structure. This is an ordered reversible thermodynamic process. Now if the transformation is halted in between, there would still exist several different variants. If such a specimen is heated above A_f, the process reverts via reverse thermoelastic transformation. The transformed variant returns to correspondence variants in the parent phase and maintains the original orientation. The detailed thermodynamic description is out of scope of this report. This phenomenon causes the specimen to revert completely to the shape it had before deformation.

Note that in presence of crystal defects, the shear also causes, to some extent, non-reversible deformation called 'slip'.

2.3 Shape Memory Effect : Characteristics

Let us look into various aspects and characteristics of the shape memory effect.

2.3.1 One Way and Two Way Shape Memory

Normally, in SMAs, only the austenitic phase orientation of the variants is memorised. Thus the material exhibits shape memory only upon heating. Once the specimen returns to its memorised state it retains it even on re-cooling. This is referred to as one way shape memory (see fig. 2.5 : Residual deformation due to loading-unloading is restored by heating to a temperature above A_f).

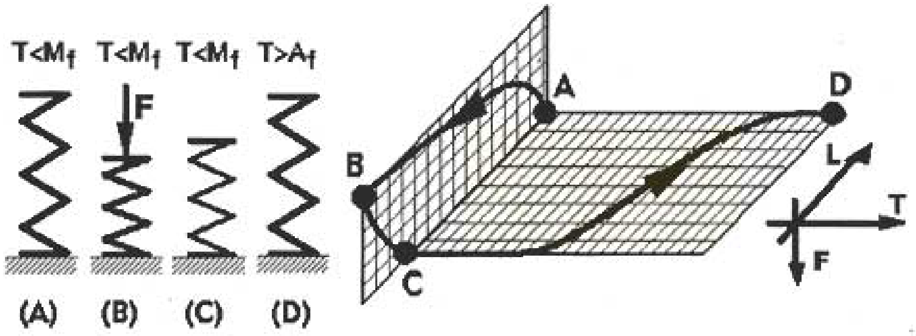


Figure 2.5: One Way Shape Memory Source: Ref. [18]

However, shape memory materials can be trained to have two way shape memory effect. Here the material memorises two shapes: one corresponding to the austenite phase and another to the martensite phase. The shape changes every time the phase changes. Note that one way memory is an inherent material property while two way memory is an induced property. Usually, this is achieved by heavily deforming the specimen in the martensite state or by heating the specimen under constraint after it has been deformed in the martensite state. Basically, the above processes create sites of internal stresses in the parent phase. These sites then control the martensitic transformation instigated by cooling. In this way the shape of martensite phase can also be partially memorised (see fig. 2.6).

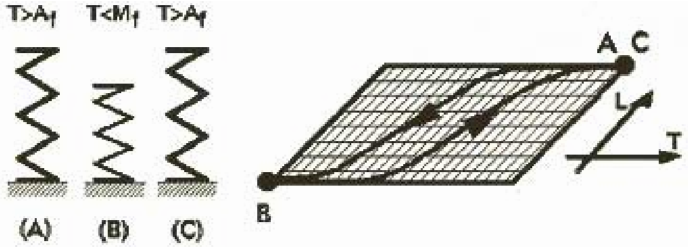


Figure 2.6: Two Way Shape Memory Source: Ref. [18]

2.3.2 All Round Shape Memory

If the composition and heat treatment is specifically arranged, some materials show 'all round shape memory effect' (ARSME). This effect is a special case of the reversible shape memory effect. Here, a continuous and spontaneous shape change takes place (unlike in two-way shape memory effect, where the changes are abrupt and instantaneous). This effect is caused due to intermediate phase transformations. The martensitic transformation within the specimen takes place at different locations in large number of stages (unlike the normal SME, where the transformation spreads at about one-third the speed of elastic wave in the medium). The shape changes involved in all round shape memory effect are large compared to the normal reversible effect.

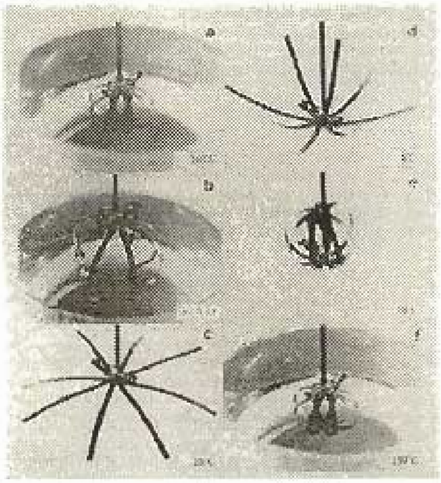


Figure 2.7: All Round Shape Memory Source: Ref. [5]

Chapter 3

Superelastic Effect, Properties and Characterisation

Apart from the shape memory effect discussed in the last chapter, shape memory alloys also exhibit some unique physical characteristics which make them the material of choice. One such interesting feature is the 'superelastic effect' where large strains are recoverable isothermally. Other unique properties include non linear, temperature dependent stress-strain relation, very high fatigue life and high internal damping. In this chapter we shall discuss these properties in some detail. We shall also look into some methods used for characterisation of transformations in SMAs. Finally, we will examine the variations in the above properties under some special conditions.

3.1 Superelasticity

At a temperature moderately greater than A_f, a shape memory alloy is capable of showing 'superelastic' properties. This means that large strains produced by mechanical loadings (which appear to be plastic strain at this temperature) are simply recovered upon unloading. These strains can be as large as 8% while for conventional materials like steel, the yield strains are of the order of 0.2 to 0.3% [18].(See fig. 3.1 : Strongly deformed sample completely recovers the shape upon unloading). Note that superelastic (or sometimes referred to as pseudoelastic) applications are isothermal in nature with temperature being fixed such that $T > A_f$.

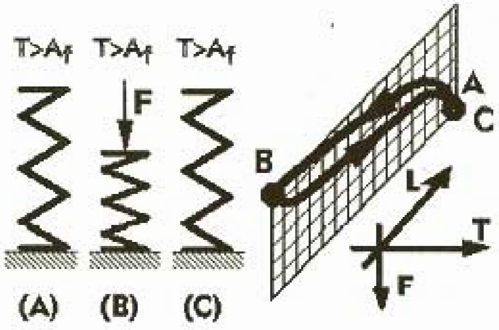


Figure 3.1: Superelastic Effect Source: Ref. [18]

3.1.1 Mechanism

We have seen that in SME, the residual strain due to martensitic transformations can be eliminated by heating the specimen above A_f. In superelastic effect, the strain at temperature above A_f can be eliminated by removing the stress.

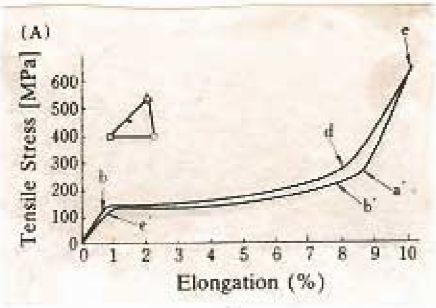


Figure 3.2: Superelastic behaviour of Cu14.1 Al4.2 Ni (wt.%) Source: Ref. [5]

Fig. 3.2 shows the stress-strain curve of CuAlNi showing superelastic behaviour. At point O, the material is in the parent austenite phase. Strains up to the point b in the curve are due to the elastic deformation of the parent phase. The stress induced martensitic transformation starts at point b. The strain increases from b to d as a result of the deformation following the stress induced martensitic transformation. From b to d, different variants begin to change into a particular variant that can yield greatest shape change in the direction of applied load. At point d, the whole specimen becomes almost a single variant martensite. The strain between points d and e is due to the elasticity of the martensite phase.

When the stress is removed, the strain level comes back to a' due to elastic recovery. Since at temperature $T > A_f$, the unstressed martensite phase is very unstable, the reverse transformation starts and continues till whole specimen regains the austenite phase. The original habit planes (which the specimen had prior to deformation) are restored and so the macroscopic strain reduces to e'. After that, an elastic recovery of the austenite phase causes complete withdrawal of strain and so the sample regains its original shape.

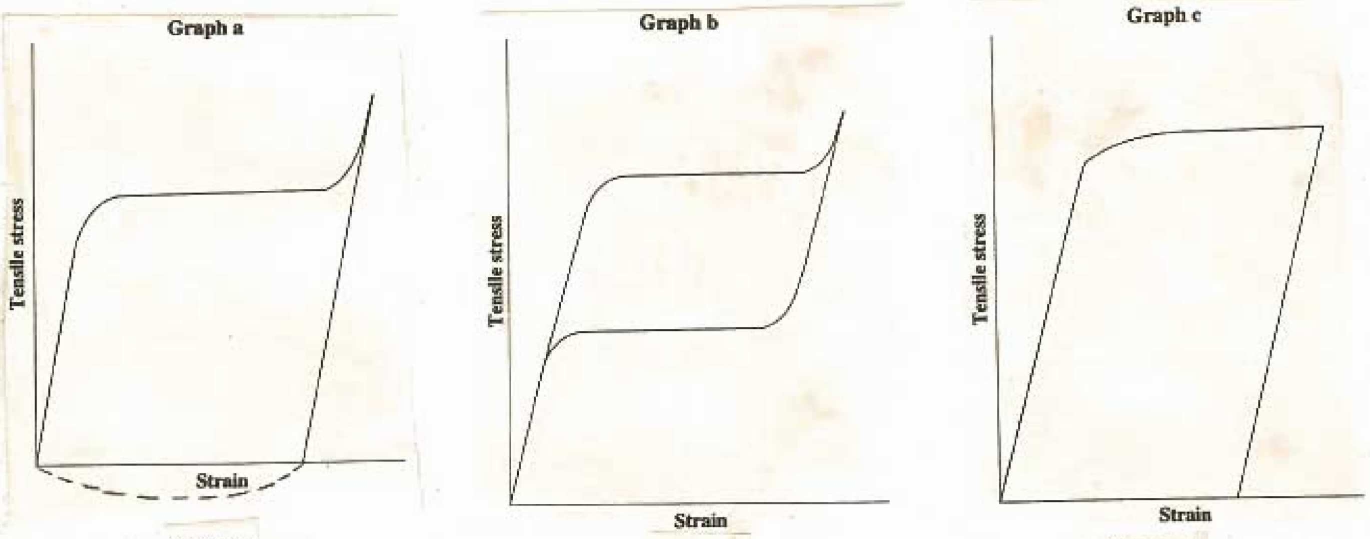
So, both in shape memory effect and superelasticity, the shape recovery is driven by reverse martensitic transformation. However, the driving force of this reverse transformation differs in the two effects.

3.2 Physical Characteristics and Properties

The physical properties of SMAs show entirely different trend from their conventional counterparts. These unique properties usually make them suitable for specific applications.(See chapter 4) Most of the properties depend highly upon the operating temperature and change drastically during transformations.

3.2.1 Stress - Strain Curves

The stress-strain relationship is highly dependent on the composition of the shape memory alloy. Also, the nature of the stress-strain curve of a particular alloy changes drastically with the operating temperature.(see fig. 3.3 (a), (b), (c)) At $T < M_f$, the specimen is entirely in



a) $T < M_f$

b) $T > A_f$,

c) $T >> A_f$.

Figure 3.3: Stress-Strain Curves of Same Alloy at Different Temperatures

martensite phase. Here, after a small elastic limit the material becomes essentially plastic. So, there are large strains induced without much change in stress values. The dashed line shows that the material returns to the original shape upon heating above A_f. (SME). At $T > A_f$, the material shows hysteresis and superelasticity. This also involves storage of potential energy. At $T >> A_f$, the material behaves much like a normal alloy. This is because the energy necessary to transform the phase is much larger than the energy necessary to deform the material. Thus, stress induced martensitic transformations cannot take place when $T >> A_f$ [2].

3.2.2 Degradation and Fatigue

In general, the fatigue lives of SMAs compared to conventional materials are found to be very large. Infinite fatigue life is observed for fairly large strain values. This property of SMAs make them advantageous to use over any other available class of structural materials. The reliability of shape memory alloys depends critically on the composition and the past history. Another major parameter that has a strong influence on the life is the heat treatment and processing that the material undergoes. Life calculation in SMAs is a complex problem. As such, no direct and simple mathematical relation exists. However, in general, it is found that the greater the shape recovery during the shape change the shorter the fatigue life of the material [4], [18].(See table 3.1) Consequently, for actuator applications, where the number of cycles required is large, materials with limited maximum stress/strain capability can be deployed [4]. On the other hand, since fasteners and pipe connectors made of shape memory alloys operate under large stresses, their fatigue lives are extremely small and can be used only once.

3.2.3 Other Properties

In addition to these, shape memory alloys have very high internal damping. The hysteresis that exists between process of forward and reverse martensitic transformation provide significant energy dissipation capabilities. Nitinol in particular has, to an extent, high im-

Table 3.1: Fatigue Life Trends in Shape Memory Alloys Source: Ref. [4]

Max. Strain (%)	Fatigue Life (cycles)	Max. Stress (MPa)	Applications
1	10,00,000	70	Two way; Actuators(long life)
4-5	10,000	140	Actuators(long stroke)
6-7	100	300	One way (Static); Connector
8	1	500	One way (Static); Coupling

pact and corrosion resistance. The electrical resistivity of SMAs also shows hysteresis (see fig 2.2). The resistivity is higher on the forward transformation and lower on the reverse transformation.

3.3 Characterisation Techniques

Many techniques have been suggested for characterising the transformation in SMAs [9]. We discuss here a few main methods among them.

Differential Scanning Calorimetry (DSC) : This technique measures the heat absorbed or given off by a small sample of the material as it is heated and cooled for transformation. As the sample absorbs or gives off energy due to transformation, the endotherm and exotherm curves are measured for the whole process of phase change.

The second method is a more direct one. Here a sample of alloy is kept under constant stress. Transformations are carried out by varying ambient temperature. (See fig. 3.4) Strain is measured while transforming in both directions. Thus, values of transformation points are obtained.

In another method, the stress-strain properties are measured in a standard tensile test at a number of temperatures across expected transformation temperature range. From the change in properties, approximate transformation temperature values can be interpolated. This is a crude but simple method and is rarely used.

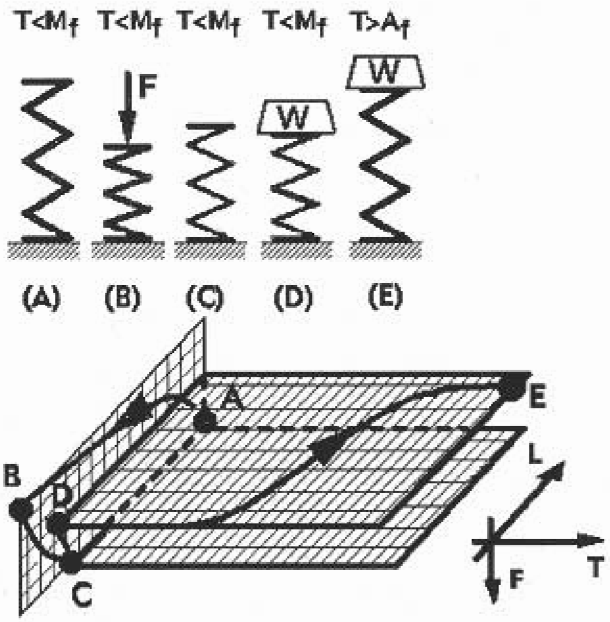


Figure 3.4: Measurement of strain under constant stress during martensitic transformation
Source: Ref. [18]

3.4 Effects of Additives and Impurities

Small variations in compositions cause substantial change in properties of shape memory alloys. These changes in composition are sometimes deliberate and sometimes accidental and undesirable. We look into some major effects seen in Nitinol.

(*i*) Fe substitution in Nitinol lowers the transformation temperatures substantially. Cu does not change the shape memory properties, but it causes a reduction in hysteresis $(A_s - M_s)$. Also, it improves the tensile strength and other mechanical characteristics [9].

(*ii*) The introduction of carbon in Nitinol affects the M_s temperature. TiC precipitate forms and cause slight degradation in tensile properties but improves fracture properties by rendering increase in fracture stress and strain [5].

(*iii*) Excess additions of Ni (upto 1%) in Nitinol strongly depresses the transformation temperature and increase the yield strength in the austenite [9].

(*iv*) Manganese often depresses the transformation temperatures of Cu based SMAs like CuZnAl and CuAlNi. It often replaces aluminum for better ductility [9].

(*v*) Boron, cerium, cobalt, iron, titanium and zirconium are added in copper based alloys for grain refinement [9].

(*vi*) Oxygen, when higher than 0.61%, may cause an intermediate phase in Nitinol. In general, it is detrimental to mechanical characteristics and makes the TiNi alloy more brittle.

(*v*) Hydrogen lowers the M_s temperature of TiNi and causes sharp change in electrical resistivity but has little effect on the actual shape memory behaviour [5].

(*vi*) Nitrogen implantation improves the corrosion resistance of TiNi but does not affects the shape memory behaviour [7].

3.5 Effects of Cycling

1. **Thermal Cycling:** The behaviour of a typical SMA under compression when subjected to thermal cycling was studied [14]. The following observations were made:

   (*i*) Even with a strong stress, the shape memory effect is only slightly decreased. The transformation temperatures are virtually unchanged.

   (*ii*) Up to a small value, the effect is linearly dependent on applied stress; above a certain value it saturates.

   (*iii*) Creep like deformation was observed.

2. **Mechanical Cycling:** The behaviour of a typical SMA was studied on mechanical cycling under constant temperature [19]. As the number of cycles were increased the following observations were made :

   (*i*) The critical stress required for inducing martensitic transformation decreases.

   (*ii*) The hysteresis effect diminishes considerably.

   (*iii*) The residual deformation increases. This may be taken as reduction in superelasticity.

Chapter 4

Applications of Shape Memory Alloys

During the last few years, a wide variety of applications of shape memory alloys have emerged both in form of products and concepts. This chapter attempts to categorise these major applications. Many interesting examples are discussed to give a feel of the unparalleled benefits of SMAs. Before that, certain guidelines of usage are discussed, which should be followed in general for any commercial realisation of these applications.

4.1 Guidelines for Using SMAs

4.1.1 Material Processing

We have already seen the effects of various additives on the properties of some common SMAs. Likewise, selective work hardening and proper heat treatment can greatly improve their structural properties. As mentioned earlier, two way shape memory effect (TWSME) can also be induced by undertaking suitable processing. Recently, 'Electromagnetic nozzleless melt-spinning method' has been proposed [15]. This method is characterised by electromagnetic float melting followed by control flow of metal with rapid solidification. This method aims at enhancing the shape memory effect in conventional TiNi alloy and developing ultra-high temperature SMAs with transformation temperatures of order of 1000^oC. Efforts are underway to develop very thin wires and films by vapour deposition [6]. The exact nature of the process differs from one application to the other. The detailed discussion is out of the scope of this report and can be found in references [5] [15].

4.1.2 Precautions

Although SMAs show shape recovery upto substantial strain levels, beyond a certain point they develop non-recoverable changes. The maximum recoverable strain depends upon factors such as heat treatment, number of cycles of operation and component's shape and dimension. A rough estimation shows that maximum strain level should not exceed 6% in case of TiNi and 2% for Cu based SMAs. For applications involving large number of cycles of operation, the values are 2% and 0.5% respectively [5].

Overheating of SMAs for long periods is also undesirable. This may cause 'blurring' of alloy's memory. Also, this causes deleterious effects on strength and other mechanical properties of the material.

4.2 Application of the Phenomena

Most commercial applications of shape memory alloys can be grouped into three broad categories.

1. **Shape Memory Actuation Devices:** These utilise the shape memory effect discussed in Chapter 2. These are further divided into three categories.

   (*i*) Free recovery: This is illustrated when SMA is deformed while it is martensitic and the only function required of the shape memory is that upon heating, the component returns to its original shape while doing minimal work.

   (*ii*) Constrained recovery: This includes applications in which the memory element is prevented from changing shape and thereby generates stresses upto 800 MPa. [18]

   (*iii*) Partially constrained: Here motion against a biased force takes place while shape recovery. Thus work upto 5 Joule/gram is obtained from the partially constrained SMA. [18]

2. **Superelastic Devices:** As discussed in chapter 3, the elasticity of SMAs is far more than the conventional materials. They can provide a constant force over a large strain range. They also have excellent torqueability and kink resistance. These properties are also exploited in various applications.

3. **Martensitic Devices:** The martensitic phase in SMAs have excellent damping characteristics along with remarkable fatigue strength. They can be easily deformed plastically, yet strains are recovered upon heating. These unique qualities form the basis of many commercial applications.

4.3 Examples

4.3.1 Aerospace Applications

1. Transportation of large sophisticated apparatus such as a radio antenna to space is extremely problematic. Incorporating the shape memory material in the fabrication, the antenna is deformed to minimum possible volume. Once the satellite is launched and reaches the stable orbit, the antenna is warmed. It then unfolds to the original shape imprinted on its memory [13]. (See fig. 1.1)

2. SMA wire tendons can be used as embedded actuator elements to control the shapes of parts such as elevators and ailerons [16]. Strain in the embedded shape memory wire is varied to control the curvature and magnitude of tip deflection. Selection of maximum variation in shape is driven primarily by required life of adaptive structures and associated fatigue limitations of SMA actuators. (See fig. 4.1)

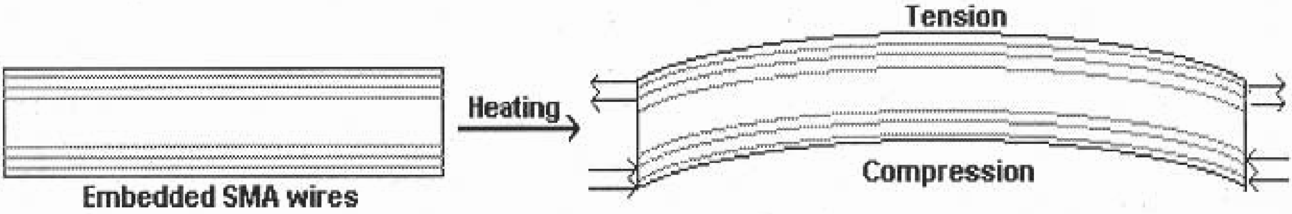


Figure 4.1: Active Shape Control Using SMAs

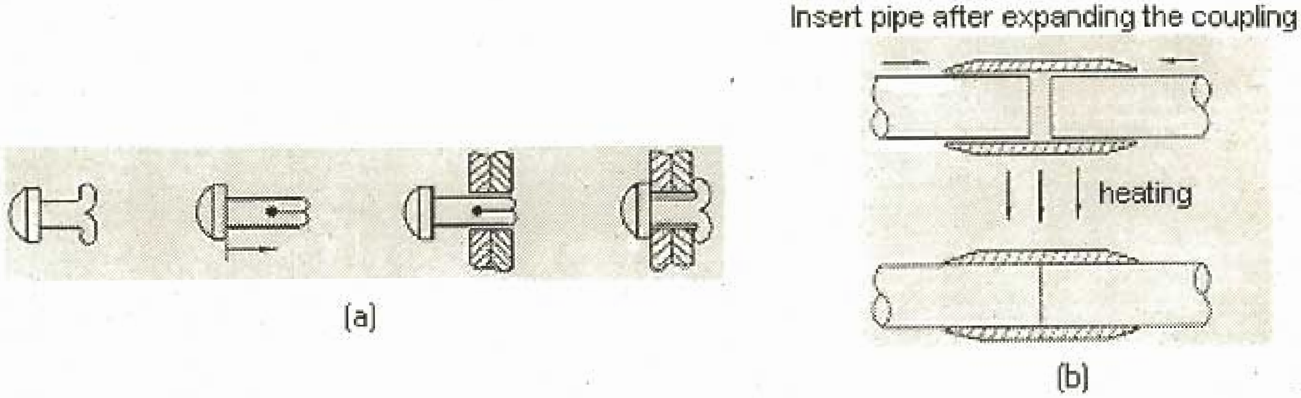
3. Structures made of composites, with brittle polymer matrix, lack a mechanism for dissipating impact strain energy. Impact type loading thus causes severe damage. SMAs have large dissipation capabilities due to the hysteresis effect. Embedding or laminating layers of superelastic SMA wire/epoxy composite in the main composite has

been shown to be effective in increasing the impact energy needed to cause damage [2], [16].

4. With the use of quick connect-disconnect connectors, it is possible to have non-explosive triggering of auxiliary fuel tank and satellite release. This is a far more simpler and safer mechanism over the conventional method in which the connectors were removed by means of explosion [16], [21].

4.3.2 Industrial Applications

1. Connectors and Fasteners: Shape memory fasteners are useful as they may be used for free-force insertion and withdrawal applications [9]. They can resist forces as high as 800MPa. They are also useful if only one side of the fastened side is accessible.(See fig. 4.2(a)) Shape memory pipe couplings are also used as shown in fig. 4.2(b). The coupling is cooled and the two ends of the pipe which are to be fixed are inserted inside. The coupling, upon reaching room temperature contracts, holding the pipes tightly [5].



(a) (b)

Figure 4.2: Shape Memory fasteners and Couplings Source: Ref. [5]

2. Monolithic Microgripper: The concept of monolithic SMA is to integrate all the functionality of a device within the same piece of material. So, the SMA is no longer a part of some mechanism but a mechanism by itself. Microgrippers and tweezers are

developed by NASA. They are used to remove small foreign objects through incisions. Two way shape memory effect is used to obtain gripping and releasing mechanism.

3. Nitinol is being used in robotics actuators and micromanupulators to simulate human muscle motion [12], [21]. Apart from compactness, smoothness in operation is obtained because the quantity controlled by the electric current is the force (from shape recovery) and not the motion.(See fig. 4.3)

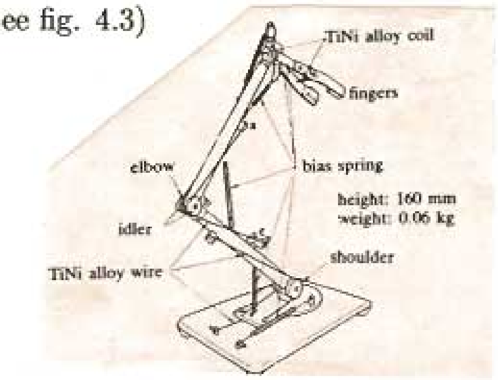


Figure 4.3: Shape Memory Actuators for Robots Source: Ref. [5]

4. Actuator for Gas-Flow Control Valve: SMA actuator system for controlling gas flow has been developed [6]. Thin TiNi films recently developed have increased the response speed to about 100Hz [6]. Accurate position control along with small response time enables the possibility of delicate flow control.

4.3.3 Biomedical Applications

1. Orthodontic Archwires: These use the superelasticity property of SMAs. When deflected, these superelastic archwires will return gradually to their original shape exerting a small and nearly constant force on the misaligned teeth. This results in enhanced comfort and faster tooth movement [21].

2. A prime application of the free recovery property of SMAs is the blood clot filter [21]. The TiNi wire is first cooled and introduced into the vein. As it warms up to the blood temperature, it forms a filter inside the vein and catches the passing clots.

Other practical biomedical applications are in the field of orthopedics and implants. All materials used for biomedical operations need to be biocompatible. Ongoing research has shown attractive results and a bright future.

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