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Synthesis and Thermo Mechanical Behaviour of Shape Memory Alloys: A Review

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Abstract: Shape memory alloys (SMAs) are a novel functional material and have found increasing applications in many areas. They are a unique class of materials with the ability to recover their shape when the temperature is increased. This paper synthesizes information on the properties, synthesis methods, characterization techniques and applications of Shape Memory Alloys and its useful aspect towards utilization in various fields.
Keywords: Shape memory alloy, phase transformation, thermo mechanical behaviour, stress- strain diagram

I. INTRODUCTION

Our encompassing is brimming with otherworldly materials. These materials are obliged to bring into presence & structure according to our need. These enchantment materials are decently explained as savvy materials & some of the time astute as well, as they can sense, function, avoid or stimulate a reaction. Smart Materials have great property of being modified. A shape-memory alloy is an alloy that regain its unique shape and when disfigured comes back to its pre-deformed shape when heated. However, when the material is heated over its change temperature it experiences a change in crystal structure which makes it come back to its unique shape. In the event the Smart Memory Alloy experiences any safety amid this change, it can create greatly substantial powers. This marvel gives a special mechanism for remote activation. This material is a lightweight, robust state option to ordinary actuators, for example, pressure driven, pneumatic, and engine based frameworks. Shape-memory combinations have applications in commercial enterprises including auto, aviation, biomedical and mechanical autonomy. [1][2][3][4][5]

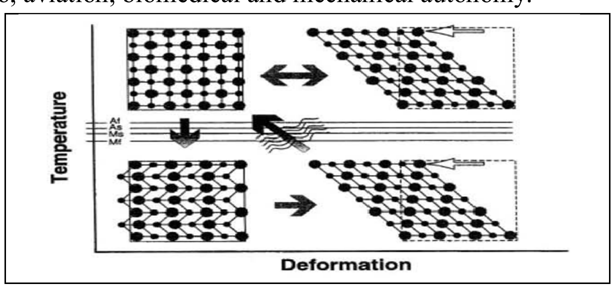

Fig. 1 Schematic representation of the shape memory effect

The fig.1 depicts that at temperatures beneath the change temperature. Shape memory alloy are Martensitic. In this condition, their microstructure is portrayed without anyone else's input "pleasing twins", The Manensite is delicate and can be disfigured effortlessly by de-twinning. Heating over the transformation temperature recoups the first shape and proselytes the material to its high quality, austenitic, condition. [6][7]

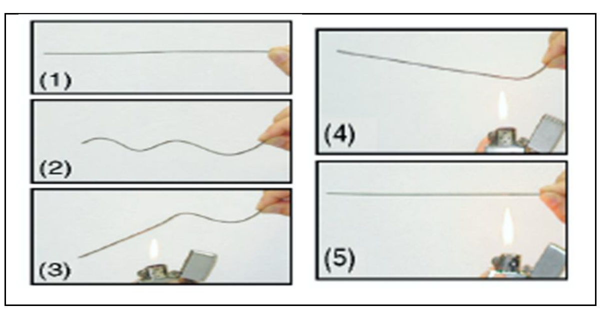

Fig. 2 A series of photographs showing the shape-memory effect: (1) the wire is straight in the parent phase; (2) the wire is

deformed in the Martensitic state; (3)–(5) the wire reverts to its original shape upon heating to a temperature at which the reverse transformation finishes. [8][9]

II. THERMO-MECHANICAL BEHAVIOUR AND PHASE TRANSFORMATIONS

The principal phenomena of the shape memory effect spoke to by the thermoelastic behavior of the martensite stage was comprehensively reported after years by Kurdjumov and Khandros in 1949 and after that by Chang and Read in 1951. In 1960s Buehler and Wiley at the U.s. Oceanic Ordinance Laboratory discovered the shape memory impact in an equi-nuclear blend of nickel and titanium, which can be seen as an accomplishment in the field of shape memory materials.[10] Shape memory composites are portrayed by a strong state phase change, in which both the beginning phase (or parent phase, called austenite) and the final phase (or item phase, called martensite) are robust structures, despite the fact that with distinctive crystallographic game plan.[11] These two stages comprise of a BCC structure for austenite, and FCC structure for martensite. The change in between these phases is known as the 'martensitic thermo-plastic transformation'. Because of the distinctive crystalline structure, austenite acts like numerous metals and has higher Young's modulus, while the martensite phase carries on additional like an elastomer, with lower solidness and a substantial "level" in its stress–strain bend (bringing about the regular nonlinear conduct of SMA). The Stable stage at any minute relies on upon the temperature connected mechanical burdens and thermo-mechanical history of the material. By varying the temperature without appling the loads, the phase of the material changes. After cooling, the material will begin from a solitary phase creation of 100% austenite to achieve a state of concurrence of both martensite and austenite in diverse extents, and finally a 100% martensite phase. At the point when heating the compound, the inverse procedure occurs.[12,13] These move temperatures increment with the connected burden in light of the fact that more vitality is obliged to disfigure the precious stone structure as an after-effect of this change, the detectable macroscopic mechanical conduct of SMA materials can be differentiated into two classes, as follows. [14] (1) The 'shape memory' Effect (SME) in which a SMA example displays a substantial leftover strain (evidently plastic) in the wake of being subjected to a heap and afterward emptied. In the wake of expanding the temperature, the alloy can totally recuperate this remaining disfigurement. (2) The 'pseudo-versatile' impact in which the SMA example displays a substantial distortion (evidently plastic) in the wake of being subjected to a heap, which can then be totally recouped by method for a hysteretic circle when emptying. Furthermore, the shape memory impact can be of two separate sorts:

(1) one-way shape memory;

(2) two-way shape memory.

The first class alludes to SMA materials for which a distorted shape must be forced and upon thermal activation the initial configuration is accomplished. The second classification, rather identifies with those materials that can "recollect" two shapes, each of which can be recovered at an alternate temperature, without obliging a applied distortion. The two-way shape memory effect is normally attained to with SMA's that show lower mechanical properties and after far reaching preparing (loading–unloading). They additionally have lower execution as actuators (lower recuperation stress when compelled). Two-way SMA's have been widely studied. [15][16][17]

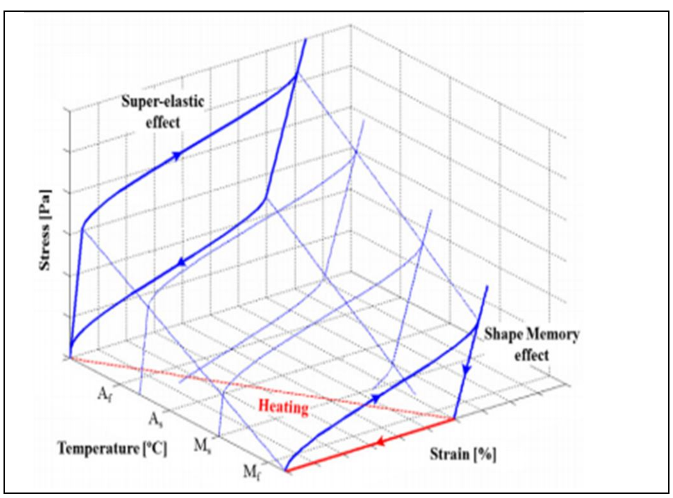

Fig3 SMA stress–strain 167ehaviour.

(a) The shape memory effect. (b) The pseudo-elastic effect.

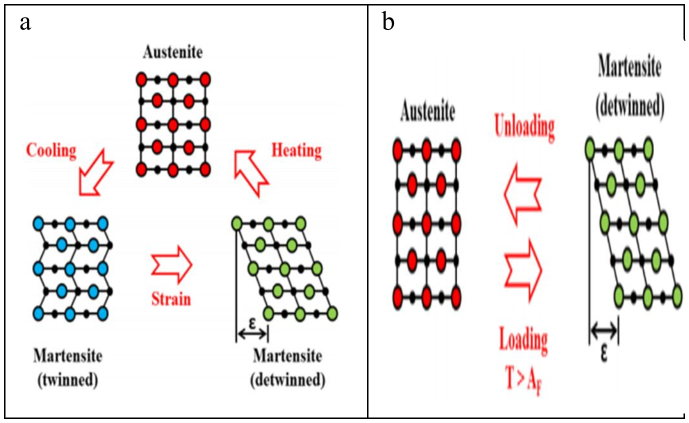

Fig 4 Microscopic phenomenology associated with the
a) Shape memory effect b) pseudo-elastic effect.

At the point when the material is loaded over the yield point in the martensite phase, as opposed to breaking the crystallographic ties, damaging its microstructure, the crystal planes slowly unfold the lattice, pleasing the strain without accomplishing significant atomic displacement. This wonder is called 'detwinning. [Fig 2 (a)][18]

The alloy can achieve the same profoundly deformable crystalline structure amid the application of an outside energy, specifically going from the austenite phase to the disfigured martensite phase. Amid Stacking, the material step by step structures the martensite structure which immediately twists, without for all time harming the crystal structure. Notwithstanding, since the stage change happens in a temperature range where the martensite phase is not steady (for T > Af the main stable stage is austenite), when the outer energy is evacuated, the alloy returns immediately to the parent phase, advancing a prompt shape recuperation.

III. STRESS STRAIN DIAGRAM OF SMA

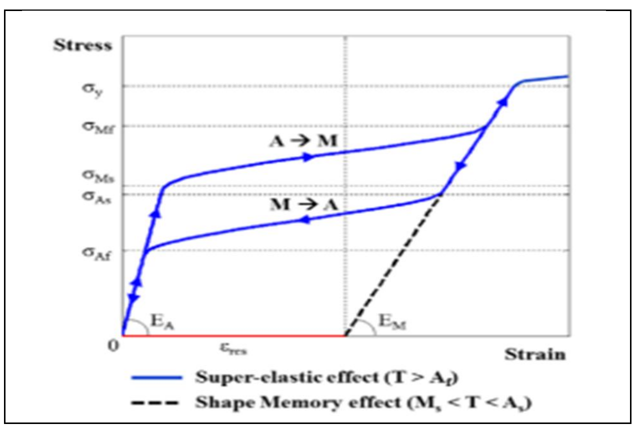

Fig 5.Typical Stress Strain Diagram of SMA

The crystal structure of martensite is acquired from austenite emulating the application of a mechanical load or a reduction in temperature. At that point, by heating or decreasing the connected load, the austenite phase is recuperated. In stress free conditions, some phase change temperatures (likewise called 'discriminating temperatures') can be identified as As, Af, Ms, Mf, (s: start, f: final, M: martensite, An: austenite). For most SMA's, it comes about that Af>As>Ms>Mf. Beginning from a zero stress condition, the alloy is subjected to a connected stress. At first the conduct is straight because of elasticity in the 100% austenite stage, with a Young's modulus equivalent to EA. At that point, the stage move (austenite to martensite) begains at the martensite begin stress (σMs). After the transition finishes, when the alloy is 100% martensite at the martensite finish stress (σMf), the pattern is straight again in the elastic range of the new phase (now the Young's modulus is EM), ceasing at yielding limit (σy). In an ordinary application, the heap achieves a level in the middle of σy and σMf. At that point unloading starts (dependably at a steady temperature T > Af). At first the same direct conduct connected with elastic unloading of martensite is taken after, until the austenite begin stress (σAs) is arrived at. By diminishing the connected load underneath this Stress (σAs), the phase transition starts, and proceeds until arriving at the 100% austenite phase, at the austenite finish stress (σAf). Further diminishment in stress leads once again to the introductory condition in a linear elastic style. Then again, if the loading–unloading methodology is directed at a temperature Ms < T < As, the shape memory effect happens. Here, a comparative pattern regarding the past case is emulated amid the loading procedure. For this situation the zero stress condition is arrived at with a lingering strain in the alloy. Just after heating at a temperature T > Af the material will recoup this strain and its unique shape again.

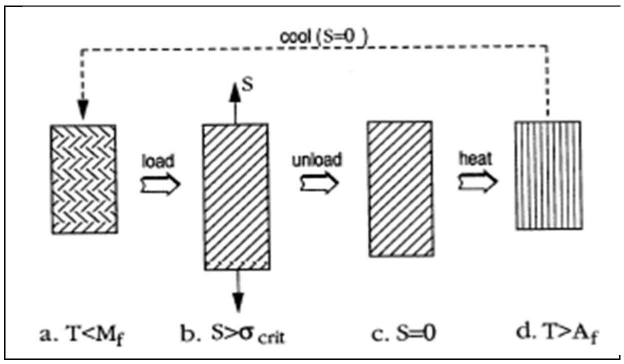

Fig6. Schematic of detwinning and phase transformation.
In (a) twinned martensite, (b) and (c) Detwinned martensite (d) Austenite [19]

IV. SYNTHESIS OF SMA

A. Ball Milling

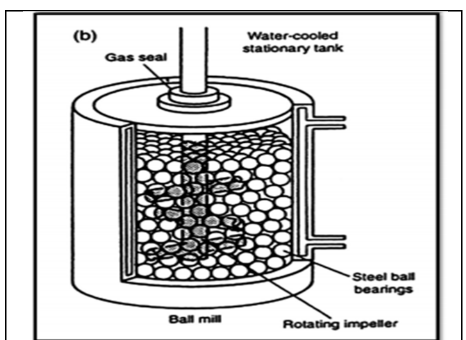

Fig 7 High Energy Ball Milling[20]

Cu, Zn, and Al powder were pure ~ 99.5% and particle size of ~100µ. We prepared sample by taking weight of each constituent and mixed it in container.Composition of mixture taken as Cu74Zn22Al4 (wt %) was mechanically alloyed in a high energy planetary ball mill using Ni-Cr steel balls as grinding media. The mechanical alloying was carried out at disc and vial rotation speed of 300 rpm, whereas the ratio of ball to powder was maintained at 3:1. For cooling the mixture liquid nitrogen was added which imparts material brittle so reduced the milling time significantly.[21][22]

B. Vacuum Induction Melting (VIM)

VIM is one of the production processes used for the preparation of Ti-Ni alloys. The technology of vacuum induction melting in graphite crucibles represents the existing key preparation method. By appropriate power control we can achieve the chemical homogeneity. During the preparation of the material in a graphite crucible it was also found that in the case of using Ni-pellets and Ti bars/disks the appropriate arrangement of the material in the crucible was important.[23][24][25] In terms VIM processing the change from high porosity graphite crucible to one with low porosity keeping its dimensions reduced the final carbon content by a factor of two.[26] The contamination due to crucible (Graphite) is the major disadvantage of the VIM process.

C. Vacuum Plasma spraying system

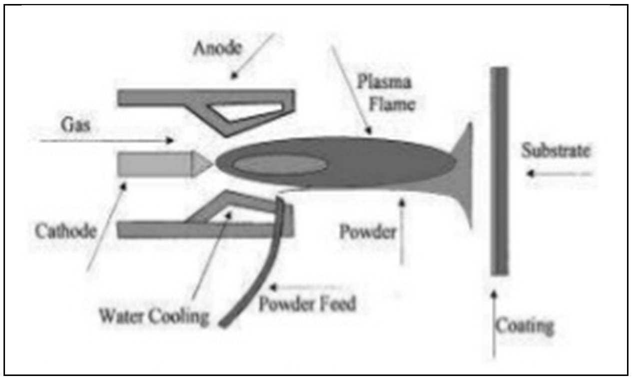

Fig8. Schematic View of Plasma Spraying system

This method succeeded in melting NiTi alloys. The plasma generated for spraying generally incorporates one or a mixture of the following gases: Argon, Hydrogen, Nitrogen, and Helium. Plasma flames can produce temperature above15000°C. The distance between the plasma jet and the cast is (15 cm), melting time (4 min) and the vacuum atmosphere is (70 mbar). The maximum electrical input power to the torch is about 50 kW. The vacuum system permits the coating production at a well defined atmosphere, which can be either vacuum or inert gas conditions. This method is successfully employed for the synthesis of NiTi Shape Memory Alloys.[27][28][29]

V. CHARACTERIZATION OF SMA

The various techniques that can be used to characterize the SMA are X-Ray Diffraction technique is used to study the identification of crystalline materials present in the sample of SMA.[30][31] SEM studies can be used to study the micrographs of the sample which shows the 3-d surface morphology of the sample with spatial resolution down to 1.4nm and with magnifying power of 10^6.[32][33] Simultaneous Thermal Analysis STA(DTA-DSC-TGA) of the sample present the thermo-mechanical behaviour of the SMA.The first step in characterizing an SMA material is to determine the characteristic transformation temperature. Actually, the material is hysteretic, and there are several transformation temperatures to speak of, including the austenite start temperature (As) and the austenite finish temperature (Af) during heating and the martensite start temperature (Ms) and the martensite finish temperature (Mf) during cooling. Additionally, an intermediate phase (R phase) often appears during cooling, having its own start temperature (Rs) and finish temperature (Rf), before the transformation proceeds to martensite at lower temperatures. With the removal of stresses, these are commonly measured by DSC thermo-grams.[34][35][36][37]

VI. PROPERTIES OF SMA

SMA properties can have a wide variability according to the chemical compositions and heat treatments to which the alloy has been subjected. Typical properties for the most widely available SMAs, such as NiTi, Cu–Zn–Al and Cu–Al–Ni alloys, are summarized in table1[12][16][38][39][40]

Table1. Variability of SMA Properties [40]

	NiTi	Cu–Zn–Al	Cu–Al–Ni
Physical properties			
Grain size (μm)	1–100	50–150	25–100
Density (g m^{-3})	6.4	6.45	7.64
Thermal expansion coefficient (10^{-6} K^{-1})	6.6–11	17	17
Resistivity ($\mu\Omega$ cm)	80–100	8.5–9.7	11–13
Damping capacity (SDC%)	15–20	30–85	10–20
Thermal conductivity (W m^{-1} K^{-1})	10	120	30–43
Normal number of thermal cycles	$>10^5$	$>10^4$	$>5 \times 10^3$
Melting temperature (K)	1573	1223–1293	1273–1323
Heat capacity (J kg^{-1} K^{-1})	390	400	373–574
Mechanical properties			
Normal working stress (GPa)	0.5–0.9	0.4–0.7	0.3–0.6
Fatigue strength ($N = 10^6$) (GPa)	0.35	0.27	0.35
Young's modulus (GPa) (parent phase)	83	72	85
Young's modulus (GPa) (martensite)	34	70	80
Yield strength (GPa) (parent phase)	0.69	0.35	0.4
Yield strength (GPa) (martensite)	0.07–0.150	0.08	0.13
Ultimate tensile strength (GPa)	0.9	0.6	0.5–0.8
Transformation properties			
Heat of transformation (J $mole^{-1}$) (martensite)	295	160–440	310–470
Heat of transformation (J $mole^{-1}$) (R-phase)	55	—	—
Hysteresis (K) (martensite)	30–40	10–25	15–20
Hysteresis (K) (R-phase)	2–5	—	—
Recoverable strain (%) (one-way martensite)	8	4	4
Recoverable strain (%) (one-way R-phase)	0.5–1	—	—
Recoverable strain (%) (two-way martensite)	3	2	2

VII. APPLICATIONS OF SMA

Materials and structures in many aerospace systems have mainly been responsible for large performance improvements, because they can reduce the gross weight and operating costs. In the future these systems have to be small, inexpensive and fast.[41] The diverse applications of SMA in diverse fields are :

A. Cellular communication

The cellular phone antenna, formerly of stainless steel, is now universally manufactured from superelastic NiTi alloy due to great resistance to permanent set on bending and accidental damage. Utilizing the same principle for manufacturing superelastic NiTi eyeglass frame, significant cold work is often used to enhance the low temperature superelasticity. Ni-rich chemistry or ternary addition is also used to achieve this desired property.[42][43]

Fig 9.Photographs of cellular phone antenna.

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B. Automobile Industry

The most recent success is the heat-to-recover NiTiNb plug for sealing high-pressure fuel passage in diesel fuel injectors.

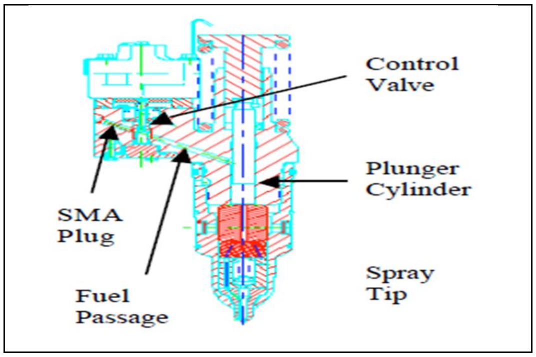

Fig10. Construction of a diesel fuel injector using SMA plug

Conventional sealing method utilizing a brazed steel plug often fails under prolonged exposure to extreme cyclical pressures. . An alternate sealing method utilizing a heat-to-recover NiTiNb plug offers a more reliable seal and can be installed at much lower temperatures than a brazed steel plug. These NiTiNb sealing plug are manufactured from rods that are longitudinally stretched to have a reduced diameter. [44][45]

C. Bioengineering Applications [46] [47]

Broken bones can be mended with shape memory alloys.

For clogged blood vessels, an alloy tube is crushed and inserted into the clogged veins. The memory metal has a memory transfer temperature close to body heat, so the memory metal expands to open the clogged arteries

Dental wires are used for braces and dental arch wires, memory alloys maintain their shape since they are at a constant temperature and because of the super elasticity of the memory metal, the wires retain their original shape after stress has been applied and removed.

D. Aerospace Applications

The Smart Wing programme was intended to develop and demonstrate the use of active materials, including SMAs, to optimize performance of lifting bodies. The project was split into two phases with the first being the most SMA intensive. Here, SMA wire tendons were used to actuate hinge less ailerons while an SMA torque tube was used to initiate span wise wing twisting of a scaled-down. [48][49][50][51].

VIII. CONCLUSION

Attention has been laid on every aspect, whether it may be the unique thermo-mechanical properties or the various synthesis methods and applications. Shape Memory Alloys are also used in applications that require lightweight construction such as in the field of aerospace, biomedical sector. SMAs possess the unusual characteristics of either SME or pseudo elasticity. These unusual properties, if properly manipulated, can bring about the era of extensive recuperation stress. Integrating SMAs into composite materials has the potential to create hybrid composites with smart capabilities and hence improved performance. Their biocompatibility trademark is being utilized in surgical instruments, in cardiovascular, orthopedic and orthodontic gadgets, and in applies autonomy and satellites. The novel properties of SMAs can likewise be effectively exploited for future work in varying fields so SMA’s can be proposed as promising candidate for Material Science.

IX. ACKNOWLEDGMENT

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