Review on Shape Memory Alloys, Processing and Applications

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Abstract - *Shape memory alloys are very important and unique class of materials with the ability to recover their original shape by increasing the temperature. In this review paper, we have focused on the various aspects of shape memory alloys like history, properties, classification and microstructure. Also, we have compared the properties of shape memory alloys with the conventional alloys. SMAs can be formed by various processing techniques. The four main categories of processing of shape memory alloys have been discussedhere. These categories include melting route, powder metallurgy processing, thermomechanical processing and mechanical processing. Due to the excellent properties, SMAs have applications in various fields and are considered as smart materials. This includes the applications in aerospace, automotive, robotics, medical, civil structures and transportation.*

Key words: Smart materials, Melting, Powder metallurgy, Thermomechanical treatment

1. INTRODUCTION

Shape Memory Alloys (SMAs) are a unique class of materials that can recover their shape when the temperature increases. It may also be named memorymetal, memoryalloy, smartmetal, ormuscle wire. These unique materials continued to intensify the accomplishment as per the need for the engineering field generally; shape Memory alloys are into heavy engineering because of properties like higher strength, higher strain recovery, lightweight, high stability etc. The most used SMA is Ni-Ti. Other examples include Ag–Cd, In–Th, Cu- based

.alloys (Cu–Zn, Cu–Zn–Al, Cu–Al–Ni), and ferrous alloys (Fe-Ni–C,Fe–Mn–Si).

Shape-memory effect and super elasticity are exhibited by the advanced material known as shape memory alloy. These properties are the reason they are different from the other materials. The shape memory effect deals with the returning of the material to it's original shape during heating after being deformed; in other words, the ability of the material to regain its shape on thermal load. This property makes them capable to recover its actual shape upon heating to a critical temperature after being deformed. Super elasticity deals with recoverable strains which are non-linear during a mechanical loading andunloading cycle.

The two types of SMA (Shape Memory alloy) based on the shape memory effect are one-way shape memory alloys and two-way shape memory alloys. Former exhibits that the metal can be deformed when it is in an unconscious state. This will retain the shape until the heating level reaches temperature called the transition temperature. In the latter one, the materials reflect one of their properties when cold and another when heated.

SMA application has been increased in recent years, the main reason for it is the availability of SMA materials with better characteristics and improved quality, together with reduced production costs. These recent changes have promoted the spread of this type of material into different technological areas and the generation of new business opportunities and new research fields. Several applications are in aerospace, civil and mechanical engineering, and military and medical devices, among many others.

DIFFERENCE BETWEEN SMAs AND CONVENTIONAL ALLOYS

The martensite to austenite transformation depends only on two factors namely temperature and stress. It is independent of time, as diffusion is not involved here.

Steel does not have shape-memory properties because martensite can be formed from austenite by rapidly cooling carbon-steel, and this process is not reversible. The SMA depicts lower yield strength than that of conventional steel, but there are some compositions that have a increased yield strength than aluminum or plastic.[5]

One of the biggest advantages of using shape memory alloys is the level of recoverable plastic strain induced. [8] The maximum recoverable strain SMA can hold without permanent deformation is up to 8% for some alloys, which is significantly higher than the conventional steels with a maximum strain of 0.5%.

	Stainless Steel	Nitinol
Density, ρ	7500 kg/m^3	6450 kg/m^3
Thermal Conductivity, k_s	29 W/m K	18 W/m K
Heat Capacity, c	630 J/kg K	620 J/kg K
Melting Temperature, T_m	1400 K	1310 K
Vaporization Temperature, T_v	3134 K	2760 K
Latent Heat, Melting, L_m	0.2×10^6 J/kg	0.2×10^6 J/kg
Latent Heat, Evaporation, L_v	7.6×10^6 J/kg	7.6×10^6 J/kg

Figure 1 Comparison of Properties between SMAs and Conventional Alloys [2]

Figure 1 compares the properties between shape memory alloy and conventional alloy as shown. Density, thermal conductivity, heat capacity, melting temperature and vaporization temperature of stainless steel is some what higher than that of the Nitinol. Latent heat of both melting and evaporation were found to be equal for bothmaterials.

2. PROPERTIES OF SMA

As we discussed above, Shape Memory Alloys had unique properties before Martensitic and Austenitic transformation. As a result of this transformation, the observable macroscopic mechanical behavior of SMA materials can be separated into two categories, as follows.

1) Shape memory alloy specimen experiences a substantial residual strain after given a load and then unloaded in 'shape memory effect'. After increasing the temperature, the alloy can completely recover this residual deformation. [10]

2) The 'pseudo elastic effect', in which the SMA specimen exhibits a very large deformation (apparently plastic) after being subjected to a load, which can then be completely recovered by meansof a hysteretic loop when unloading. [10]

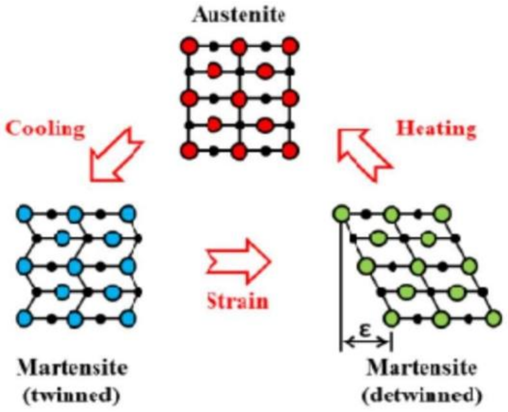

Figure 2 Microscopic phenomenology associated with the shape memory effect.

Both effects (SME and pseudoelasticity) can be summarized in a single stress-strain diagram, as shown in figure 4[1], although for different temperatures. The pseudoelastic effect can be observed for an SMA tested at a temperature T > Af, which is represented by the solid line. The SME is shown as a segmented line. Starting from a zero- stress condition, the alloy is subjected to applied stress. Initially, the behaviour is linear due to elasticity in the 100% austenite phase, with a young's modulus equal to EA.

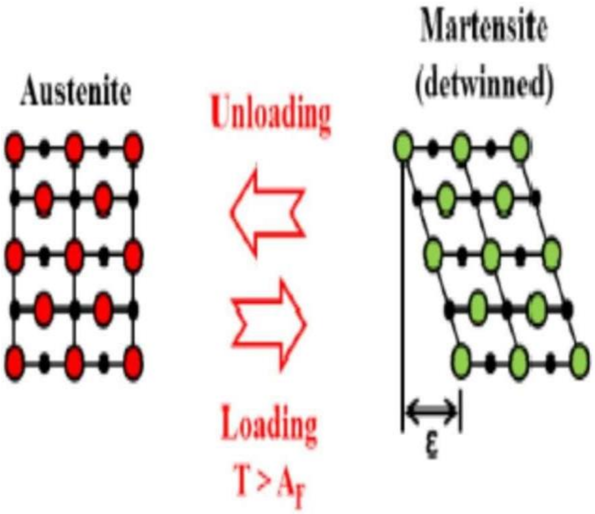

Figure 3 Microscopic Phenomenology associated with Pseudo Elastic Effect

The above two diagrams [figure 2 and figure 3] indicate the microscopic phenomenology involved with the shape memory effect and pseudo-elastic effect. It describes the effect of loading and unloading of a material.

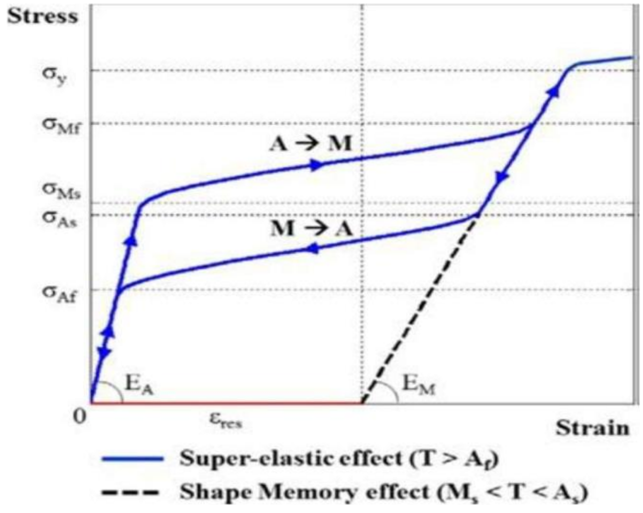

Figure 4 Typical SMA stress–strain diagram

Then, the phase transition (from austenite to martensite) begins at the martensite start stress. σMs/. After the transition finishes when the alloy is 100% martensite at the martensite finish stress. σMf/, the trend is linear again in the elastic range of the new phase(now the young's modulus is EM), stopping at the yielding limit (σy).

In a typical application, the load reaches a level between σy and σMf. Then unloading begins (always at a constant temperature T > Af). The same linear behaviour associated with elastic unloading of martensite is followed until the austenite starts to stress. σAs/ is reached. [32]

By decreasing the applied load below this stress. σAs, the phase transition begins and continues until reaching the 100% austenite phase, at the austenite finish stress. σAf. Further reduction in stress leads back to the initial condition in a linear elastic fashion. On the other hand, if the loading-unloading process is conducted at a temperature (Ms < T < As) the shape memory effect takes place.

A similar trend concerning the previous case is followed during the loading process. In this case, the zero-stress condition is reached with a residual strain in the alloy (εres). Only upon heating at a temperature T >Af will the material recover this strain and its original shape again. [11]

Figure 4 shows the typical shape memory alloy stress-strain diagram. It describes both shape memory effect and pseudo-elastic (super-elastic) effect due to the effect of loading and unloading, where A stands for austenite and M stands for martensite.

3. CLASSIFICATION OF SHAPE MEMORY ALLOYS

Over the years, shape memory alloys have been classified in various ways. It can be classified by means of its properties like shape memory effect and superelasticity, by the material from which it has been made like Ni-Ti shape memory alloys, Copper-based shape memory alloys, Iron-based shape memory alloys. Shape Memory alloys can be broadly classified into three types as follows.

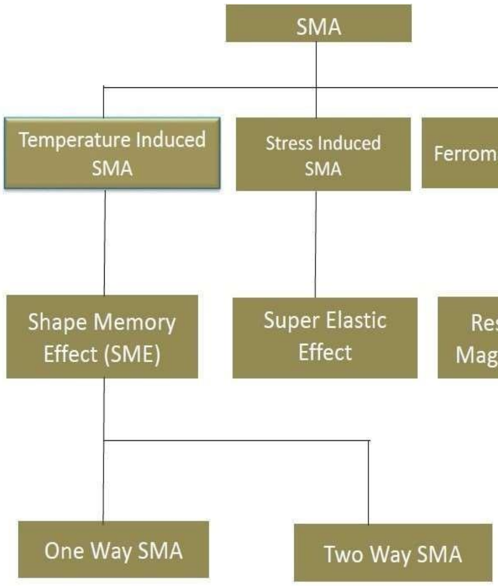

Figure 5 Classification of SMAs

Temperature Induced Shape Memory Alloys

Temperature induced shape memory alloys includes shape memory effect and based on that as per figure 5, there are two types of shape memory alloys namely one-way SMA and two-way SMA. The materials that demonstrate shape memory effect by returning back to their original shape upon heating are known as one way shape memory alloys. Conversely, some materials that depicts shape memory effects during both heating and cooling are referred to as two-way shape memory alloys.[11]

The initial configuration is attained in one-way SMA after imposing deformed shape and upon thermal activation. In two-way SMAs, the material remembers two shapes which can be recovered at different temperature independent of the subjected deformation. The SMAs that exhibits lower mechanical properties and after substantial loading and unloading, two-way shape memory effect is achieved. [17]

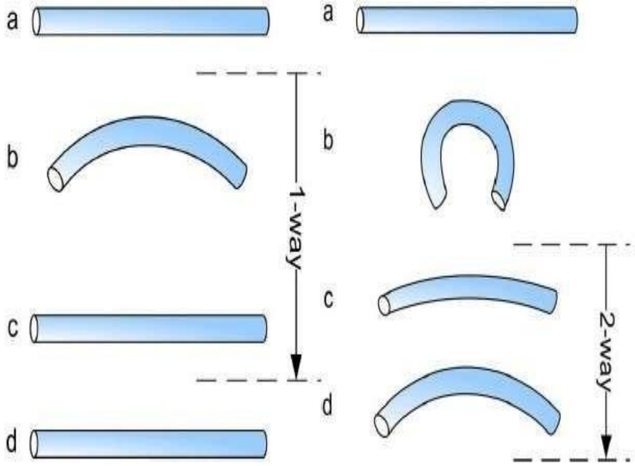

Figure 6 One-way and two-way effect

Ferro Magnetic Shape Memory Alloys

Ferro Magnetic Shape Memory Alloys are that type of SMAs that shows a shape-memory effect in response to a magnetic field. They are also known as Magnetic Shape Memory Alloys (MSMA). [16] Deformation that occurs due to a magnetic field is known as magnetoelastic deformation. Some examples of Ferromagnetic SMAs are Ni_2MnGa, Fe-Pd, Fe_3Pt.

Magnetic shape memory alloys are those kinds of ferromagnetic materials that can create motion and forces under moderate magnetic fields. Generally, Nickel, Manganese and Gallium (Ni-Mn-Ga) are used.

The large magnetically induced strain and the short response times make the MSM technology very attractive for the design of innovative actuators to be used in pneumatics, robotics, medical devices, and mechatronics. MSM alloys change their magnetic properties depending on the deformation. This companion effect, which co-exists with the actuation, can help design displacement, speed or force sensors and mechanical energy harvesters.

The magnetic shape memory effect occurs in the low-temperature martensite phase of the alloy, where the elementary cells composing the alloy have tetragonal geometry. If the temperature is increased beyond the martensite–austenite transformation temperature, the alloy goes to the austenite phase, where the elementary cells have cubic geometry. With such geometry, the magnetic shape memory effect is lost.[28]

The transition from martensite to austenite produces force and deformation. Therefore, MSM alloys can also be activated thermally, like thermal shape memory alloys. One important phenomenon in ferromagnetic shape memory alloys is the magnetic shape memory effect.

Magnetic Shape Memory Effect

The mechanism accountable for the considerable strain of MSM alloys is the so-called magnetically induced reorientation (MIR) and is sketched in the figure. Like other ferromagnetic materials, MSM alloys exhibit a macroscopic magnetization when subjected to an external magnetic field, emerging from the alignment of elementary magnetizations along the field direction. However, differently from standard ferromagnetic materials, the alignment is obtained by the geometric rotation of the elementary cells composing the alloy and not by rotation of the magnetization vectors within the cells (like in magnetostriction).[27]

A similar phenomenon occurs when the alloy is subjected to an external force. Macroscopically, the force acts as the magnetic field, favouring the rotation of the elementary cells and achieving elongation or contraction depending on its applicationwithinthereferencecoordinate system. The elongation and contraction processes are shown in the figure where, for eg., the elongation is achieved magnetically and contraction mechanically. The rotation of the cells is a consequence of the large magnetic anisotropy of MSM alloys and the high mobility of the internal regions. Simply speaking, an MSM element is composed of internal regions, each having a different orientation of the elementary cells (the regions are shown by the figure in green and blue colours). These regions are called twin variants. Applying a magnetic field or external stress shifts the boundaries of the variants, called twin boundaries, and thus favours one variant or the other. When the element is completely contracted or completely elongated, it is formed by only one variant, and it is said to be in a single variant state. [26]

The magnetization of the MSM element along a fixed direction differs if the element is in the contraction or the elongation single variant state. The magnetic anisotropy is the difference between the energy required to magnetize the contraction single variant state component and the elongation single variant state. The value of the anisotropy is related to the maximum work-output of the MSM alloy, and thus to the available strain and force that can be used for applications. [29]

4. PROCESSING OF SHAPE MEMORY ALLOYS

In this advanced, progressed and competitive technology, there are numerous types of processing methods available for a particular material. The processing routes vary in terms of manufacturing, uses, economics, efficiency, etc. In the same way there are various kinds of processing methods available for the production of shape memory alloys. Retention of shape memory effect, mechanical properties variation, microstructural changes and formation of intermetallic compounds and precipitates are the issues associated with processing of shape memory alloys as thermal and mechanical treatments affect chemical reactions and phase transformation of shape memory alloys.

The processing of shape memory alloys includes melting route, powder metallurgy processing, mechanical processing and thermo mechanical processing. Before the processing of SMA's through various routes, pre-processing steps are done for the accurate and efficient production.

Pre-processing steps needed for shape memory alloys include collection of the raw materials required, pre-cleaning, cutting and sizing of the materials in needed proportion, post cleaningand making the powder form of the material (for powder metallurgical processing).

Melting Route

The processing of shape memory alloys through melting route is further classified in four routes namely Vacuum Induction Melting, Selective Laser Melting, Electron Beam Melting and Plasma Melting.

Vacuum Induction Melting is one of the production processes used for the preparation of Ni-Ti alloys. The technology of this method in graphite crucibles represents the existing key preparation method. A crucial impact on the fast increase of metal production by this method is due to achievement of very close compositional tolerances, precise temperature control and environment friendly process. [11]

Shape memory alloys such as Ni-Ti, Cu-Al-Ni-Mn, Fe–Mn–Al–Ni, and Al–Fe– V–Si are reported as fabricated by Selective Laser Melting. It is a successful fabrication process to obtain porousshape memory alloys with better shape memory properties. It has advantage of scanning pattern of f-theta lenses that minimizes distortion during scanning process. [2]

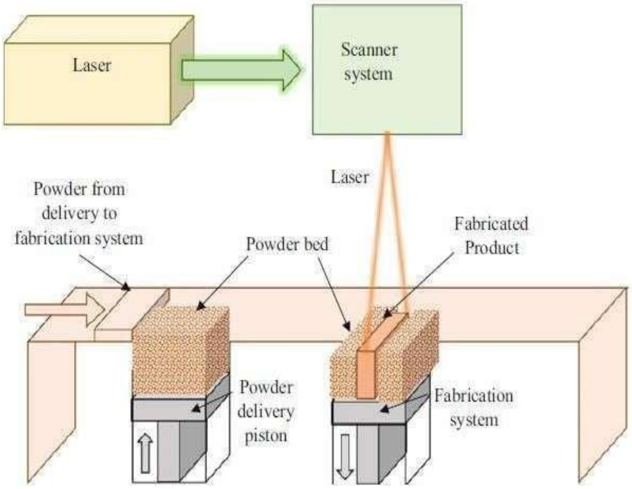

Figure 7 Selective Laser Melting Process

Electron beam melting is a layer by layer material addition manufacturing technique using electron beam.The process needs to operate invacuumchamber due to involvement of electron beam. It produces better NiTimaterialintermsofhomogeneous chemical composition and reduces carbon and oxygen contaminations as compared to Vacuum Induction Melting. [23]

Prevention of contamination of melted material by graphite from used electrodes, high concentration of energy, high plasma flow velocity and very quick heattransfer gives birth to Plasma Melting process. Instead of electrodes, plasma burners are used and the furnace used to be equipped with special soil electrode carrying the current into the charge in this method.

Powder Metallurgy Processing

Powder metallurgy processing is a conventional method of material processing in which the metal powder is processed to obtain final product without any material loss. Shape memory alloys of Ni-Ti, Cu–Al– Ni–Mn and Fe-Mn-Si-Cr-Ni are processed and investigated by different powder metallurgy techniques such as conventional sintering, hotisostatic pressing andmetal injection molding. [11]

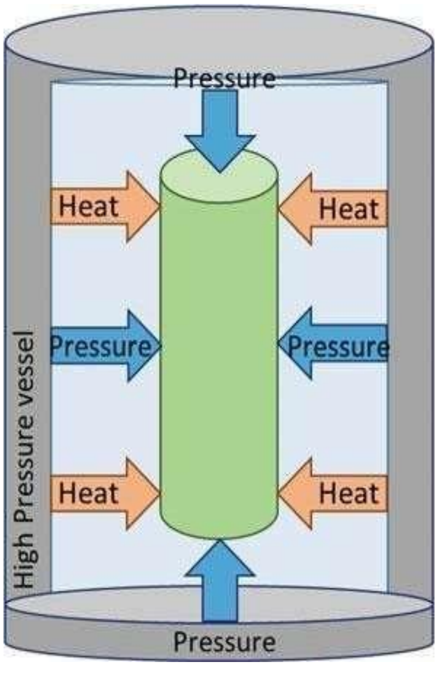

Figure 8 Hot Isostatic Process

Hot isostatic pressing is also known as pressure enhanced sintering that increases density and reduces porosity of the material, which is the major drawback of the conventional sintering process in case of shape memory alloys.[11]

Sintering is the process of fabricating solid mass of material by compacting and forming with the application of heat or pressure without melting it to the point of liquification. It is majorly applied to Nitinol.[21] There are few factors such as applied pressure, unbalance in diffusion of Ni into Ti and Ti into Ni, shrink during sintering, and capillary forces are identified that governs formation of porosity in conventional sintering of Nitinol.

Metal injection molding works on the concept of plastic injection molding. The method is operated with four steps such as feedstock fabrication, injection molding, debinding and sintering. Geometrical precision of the parts, high production value, and low cost are the key advantages of this process. It is adopted for NiTi material fabrication specifically for biomedical applications. [23]

Mechanical Processing

Here processing is done by mechanical loading that causes material deformation and leads to the change in properties. Mechanical processing such as equal channel angular extrusion, cold forging, cold rolling and cold drawing are described for the manufacturing of shape memory alloys.

In equal channel angular extrusion process, severe plastic deformation is caused by high axial pressure. This method has some key advantages such as uniform microstructure, control over grain morphology and texture, and easy processing with respect to the other processes. Transformation behavior and microstructural changes of NiTi material are greatly affected by this process.

Cold forging is a process in which the material is not heated and mechanically deformed with the help of adequate forging force. It is suggested that cold forging of shape memory alloys can be performed with small oxide layer that absorbs applied load and protect underneath material. [22]

Cold rolling is a process in which material subjected from two rollers provide compressive forces to the material. It is reported that cold rolled shape memory alloys (especially NiTi material) and subsequent annealing lead to nanostructured microstructure, which presents an excellent shape memory effect along with enhanced mechanical properties.[25]

Cold drawing is a similar type of process like extrusion and cold rolling wherein shape memory alloy rod or wire is subjected to a die to pull the material that subsequently results in an elongated grains by having decreased dimensions. The use of lubricants or protective layers is recommended for shape memory alloys that enhances the finishing and processing.

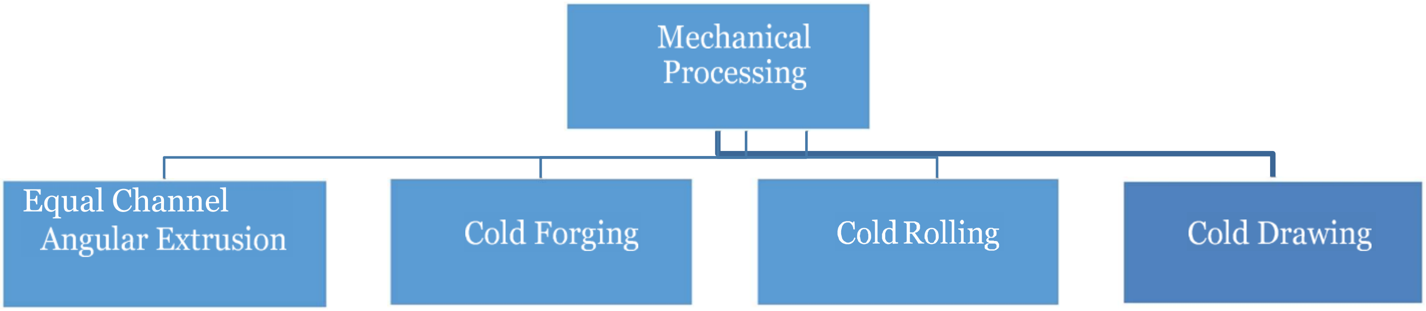

Figure 9 Classification of mechanical processing methods of SMA

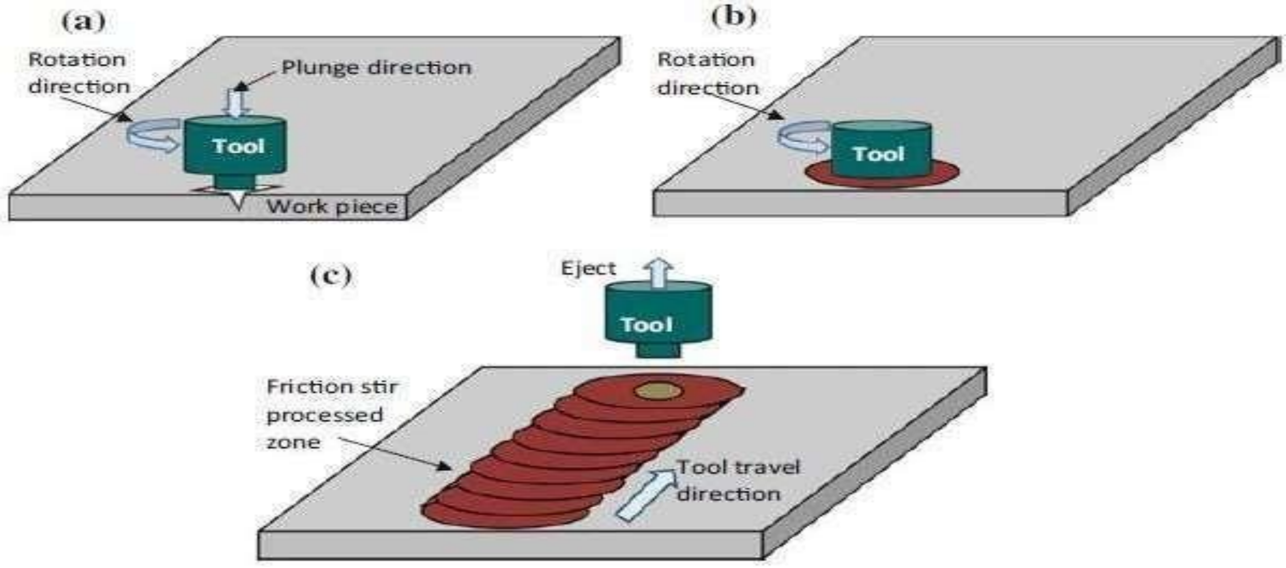

Figure 10 Friction stir processing, (a) Plunge (b) dwell and (c) processing and tool eject

Thermo-mechanical Processing

Thermo-mechanical processing is a category of fabrication processes that undergo mechanical deformation or plastic deformation process along with thermal processing effects. Friction stir processing, hot forging and hot rolling methods come under the context of thermo-mechanical processing.

Friction stir processing works on the principle of solid state processing. Fabrication of Aluminum-NiTi composite is carried out and observed that homogeneousdistributionof NiTipowder inmatrix is possible with good bonding by controlling process parameters. [11]

Hot forging is a type of thermo-mechanical fabrication process, which uses heat and forging force to deform the material that in turn form the desired shape. [32] Shape memory alloy of Ni-Mn-Ga is investigated by hot forging. It is exhibited that favorable hot forging parameters can fabricate a complex shape memory alloy part with excellent shape memory effects and without any major defects.

Hot rolling is a processing technique in which the material is heated and forced to press with rollers. It needs important process parameters such as heating temperature, pulling tension applied to the material, type of lubricant, and number of passes to control as theygovern shape memoryeffect and other mechanical properties. [24]

5. APPLICATIONS OF SHAPE MEMORY ALLOYS

Shape memory alloys have a breakthrough wide range applications all over the world. They impart uses in micro and nano industrial world. Classic properties such as free recovery or pseudo elasticity have much importance aiding in applications. They have been implemented in several high performance applications requiring high work densities, large recoverable deformations, high stresses and good bio-compactibility.

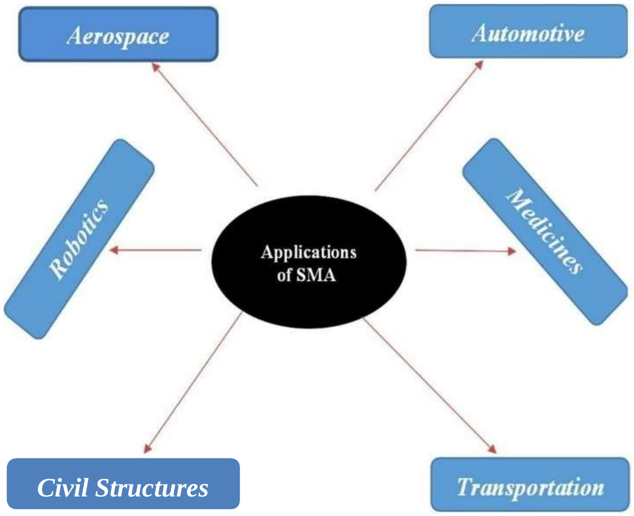

Figure 11 Applications of Shape Memory Alloys

This tire can be deformed 30 times than that of conventional alloy. [8]

SMA technology implementation in the aerospace industry has spanned the areas of fixed-wing aircraft, rotorcraft, spacecraft and work in all these areas is still progressing. Research is beingperformed into methods by which SMA beam components can be embedded insidechevrons. TheSMAbeamsbendthechevronsinto the flow during low-altitude flight or low speed flight,thereby increasing mixing and reducing noise. [3] During high-altitude, high speed flight, these SMA beam components will cool into martensite, thereby straightening the chevrons and increasing engine performance.

Shape memory alloys have their potential in the following fields:-

- Aerospace
- Automotives
- Civil Structrures
- Medicines
- Robotics
- Transportation

Aerospace

SMA's have significant use in aerospace industries. Using NiTi SMA, the Variable Geometry Chevron was developed by NASA, Texas A&M University, Boeing, Goodrich Corporation, All Nippon Airways and General Electric Aircraft Engines. Recently NASA have also developed name Spring Tire which is made up of Ni-Ti SMA.[1]

Figure 13 Spring Tire (Ni-Ti SMA)

Figure 12 Boeing variable geometry chevron, flight testing

Automotives

Many automotive manufactures are recently implementing SMAs to their vehicles. The first ever commercial SMA actuator introduced in the year 1989 for automotive application is the thermally responsivepressure control valve embedded in Mercedes-Benz automatic transmission for smooth gear shifting. The 2014 Chevrolet Corvette became the first vehicle to incorporate SMA actuators, which replaced heavier motorized actuators to open and close the hatch ventthat releases air from the trunk, making it easier to close. [13]

SMA pneumatic valves for lumbar support in car seats for Daimler Mercedes Benz was successfully mass produced by Alfmeier Prazision AG (now Actuator Solutions GmbH). [20] A variety of other applications are also being targeted, including electric generators to generate electricity from exhaust heat and on-demand air dams to optimize aerodynamics at various speeds. SMAs haveexcellent potential in various automotive functions and conditions due to their mechanical simplicity, better performance, attractive attributes and flexibility. [18]

Figure 14 SMA Air/Gas valve (Actuator Solutions GmbH)

Civil Structures

Shape memory alloys are also useful in civil structures. One such application is Intelligent Reinforced Concrete (IRC), which incorporates SMA wires embedded withinthe concrete. This cansenseand heal the cracks withinit.

They have a series of applications in structures like bridges and buildings. SMAs are also advantageous forconstructioninseismic regions. If SMAisusedas a reinforcement, it will yield whensubjected to high seismic loads but will not retain significant permanentdeformation. [14] Inrefinery and piping industries, shape memory alloys found it’s use in pipingcoupling for oil pipelines. In commercialand consumer applications, they are used in water pipelines.

Robotics

One of the main field of application of shape memory alloy is robotics. In this advanced technology, SMAs are a boon in this industry.

Medicines

Shape memory alloys are a boon to medical industry. They have numerous applications in many fields of medicine. AnimportantrequirementforanSMA,orany other material to be used in the human body, is that it be biocompatible. A biocompatible material cannot produce any allergic reaction or inflammatory response in the host. The other requirement for the material is its biofunctionality, which is the ability to function desirably for its expected service life in the human body environment. [19] These two requirements are crucial for the application of SMAs in the medical industry.

SMAs are also used in cardiovascular applications. An early cardiovascular SMA device was the Simon Filter. They are also used in eyeglass frames, it can come back to it’s original position after bending. It consists of Titanium based shape memory alloy. Here the transition temperature is set below the room temperature. [7]

Shape-memory alloys are used as a fixation devices for osteotomies in orthopaedic surgery. In a separate application, SMAs fasten to broken or fractured bones to facilitate healing. [12] These devices include orthopaedic staples and shape memory plates.

SMAs are also used inorthodontic applications. Nitinol braces are used for alignment purpose in dental applications. NiTi drill is used for root canal surgery

Figure 15 SMA in eye glass frames

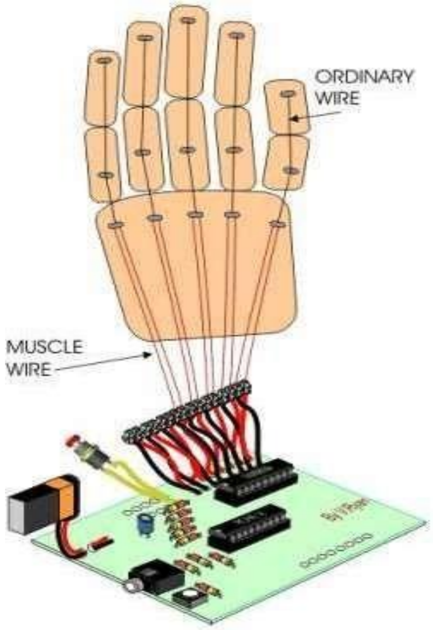

Figure 16 Shape Memory Alloy (Muscle Wire) in Robotic Hand

SMAs are mainly used as thermal – mechanical actuators in robotics applications. Hobbyist robot Stiquito and Roboterfrau Lara made it possible to create very lightweight robots. Recently, a prosthetic hand was introduced that can almost replicate the motions of a human hand [Loh 2005]. It is also used as an autofocus actuator for a smart phone. There are currently several companies working on an optical image stabilization (OIS) module driven by wires made from SMAs. [15]

Transportation

Shape memory alloys have been used in automobiles for applications ranging from impact absorption to sensing and actuation. [30] The pseudo-elastic behavior hysteresis provides an effective system to dissipate vibrations and impact. This property has been used for impact absorption on armor vehicles in military and commercial applications. A similar actuation system is incorporated in the Shinkansen bullet train gearbox where the temperature in the gear box is monitored and an SMA spring actuates a valve to adjust the oil level in the gearbox. [9]

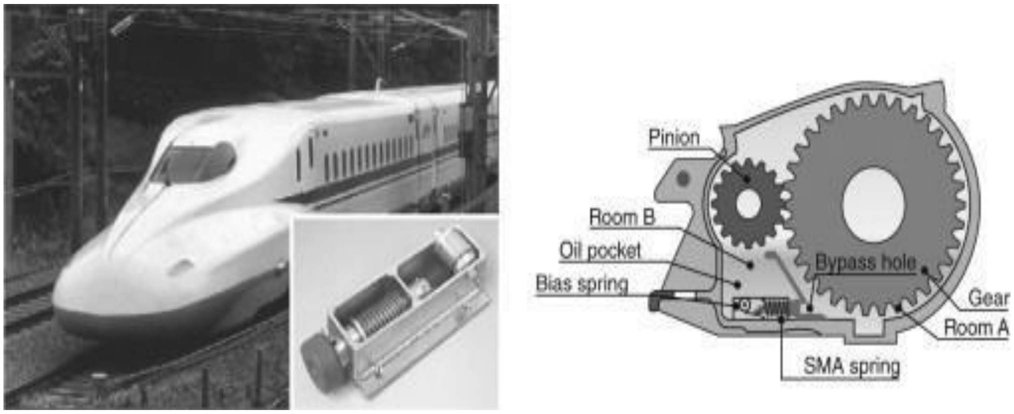

Figure 17 SMA Gearbox in Bullet Train

Other applications developed for trains include the thermally actuated switch for the radiator fan in diesel engines and steam traps for the steam heating system in passenger trains. Both applications utilize the shape memory effect.

Conclusion

In this review paper, the main aspects of shape memory alloys were discussed like properties, history, classification and microstructure. The various processing techniques of shape memory alloys include melting route, powder metallurgy processing, mechanical and thermo-mechanical treatments were focused. Due to the precious properties like recoverable strain, corrosion resistance, good ductility, light weight, etc., shape memory alloys have been used in aerospace, automotive, robotics, medical, transportation and civil structures.

The characteristics and applications of SMA makes future of these alloys. The future of shape memory alloys is bright and it's application will be incorporated in each field due to advancement in technology. Nowadays many research works are going on shape memory alloys Processing of SMA is a quite difficult task as it requires a high installation cost. Also due to poor fatigue properties, their formation is difficult.

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