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A Review on Shape Memory Alloy (SMA), Behavioral Fatigue and its Applications

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Abstract **Shape memory alloys (SMAs) are a unique class of metallic materials with the ability to recover their original shape at certain characteristic temperatures (shape memory effect), even under high applied loads and large inelastic deformations, or to undergo large strains without plastic deformation or failure (super-elasticity). In this review, we describe the main features of SMAs, their comparisons and their properties. We also review the fatigue behavior of SMAs and some methods adopted to remove or reduce its undesirable effects. SMAs have been used in a wide variety of applications in different fields.**

Keywords* — *shape memory alloys, smart materials, super-elasticity, shape memory effect, pseudo elasticity, crystal structure

I. INTRODUCTION

The increased use of sensors, actuators and microcontrollers have been necessitated by the up gradation in Technology towards smart systems with adaptive or intelligent functions and features, which results in an undesirable increase in weight and volume of the associated machine components. The technical and commercial restrictions, such as available space, operating environment, response time and allowable cost can be overcome by high functional density and smart materials. [1]. In particular, for automotive construction and design: increased mass directly results in increased fuel consumption, and automotive suppliers are highly cost-constrained. Research on the application of smart technologies must concentrate on ensuring that these 'smart' systems are compatible with the automotive environment and existing technologies [1]. The integration and miniaturisation of integrated micro-controllers and advanced software has enabled considerable progress in the field of automotive sensors and control electronics. However, the technical progress for automotive actuators is relatively poorly advanced [2]. Currently, there are about 200 actuation tasks are performed on vehicles with conventional electro-magnetic motors, which are potentially sub-optimal for weight, volume and reliability [3].

Shape memory alloy (SMA) or ''smart alloy'' was first discovered by Arne Ölander in 1932 [4], and the term ''shape-memory'' was first described by Vernon in 1941 [5] for his polymeric dental material. The importance of shape memory materials (SMMs) was not recognised until William Buehler and Frederick Wang revealed the shape memory effect (SME) in a nickel-titanium (NiTi) alloy in 1962 [6,7], which is also known as nitinol (derived from the material composition and the place of discovery, i.e. a combination of NiTi and Naval Ordnance Laboratory). Since then, the demand for SMAs for engineering and technical applications has been increasing in numerous commercial fields; such as in consumer products and industrial applications [8–10], structures and composites [11], automotive [2,12,13], aerospace [14], mini actuators and micro-electromechanical systems (MEMS) ,robotics , biomedical and even in fashion. Although iron-based and copper-based SMAs, such as Fe–Mn–Si, Cu–Zn–Al and Cu–Al–Ni, are low-cost and commercially available, due to their instability, impracticability (e.g. brittleness) and poor thermo-mechanic performance; NiTi-based SMAs are much more preferable for most applications. However, each material has their own advantage for particular requirements or applications. The two most prevalent shape-memory alloys are copper-aluminium-nickel and nickel-titanium (NiTi), but SMAs can also be created by alloying zinc, copper, gold and iron. Although iron-based and copper-based SMAs, such as Fe-Mn-Si, Cu-Zn-Al and Cu-Al-Ni, are commercially available and cheaper than NiTi, NiTi-based SMAs are preferable for most applications due to their stability and practicability and superior thermo-mechanic performance.

II. SHAPE MEMORY ALLOY OVERVIEW

SMAs are a group of metallic alloys that can return to their original form (shape or size) when subjected to a memorisation process between two transformation phases, which is temperature or magnetic field dependent. This transformation phenomenon is known as the shape memory effect (SME).The basic application of these materials is quite simple, where the material can be readily deformed by applying an external force, and will contract or recover to

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its original form when heated beyond a certain temperature either by external or internal heating (Joule heating); or other relevant stimuli such as a magnetic field for MSMAs.

III. SMA CHARACTERISTICS

The copper-based and NiTi-based shape-memory alloys are considered to be engineering materials. These compositions can be manufactured to almost any shape and size. The yield strength of shape-memory alloys is lower than that of conventional steel, but some compositions have a higher yield strength than plastic or aluminum. The yield stress for Ni Ti can reach 500 MPa. The high cost of the metal itself and the processing requirements make it difficult and expensive to implement SMAs into a design. As a result, these materials are used in applications where the super elastic properties or the shape-memory effect can be exploited. The most common application is in actuation. One of the advantages to using shape-memory alloys is the high level of recoverable plastic strain that can be induced. The maximum recoverable strain these materials can hold without permanent damage is up to 8% for some alloys. This compares with a maximum strain 0.5% for conventional steels.

SMAs can exist in two different phases, with three different crystal structures (i.e. twinned martensite, detwinned martensite and austenite) and six possible transformations.

NiTi alloys change from austenite to martensite upon cooling; M_f is the temperature at which the transition to martensite completes upon cooling. Accordingly, during heating A_s and A_f are the temperatures at which the transformation from martensite to austenite starts and finishes. Repeated use of the shape-memory effect may lead to a shift of the characteristic transformation temperatures (this effect is known as functional fatigue, as it is closely related with a change of micro structural and functional properties of the material). The maximum temperature at which SMAs can no longer be stress induced is called M_d, where the SMAs are permanently deformed.

The transition from the martensite phase to the austenite phase is only dependent on temperature and stress, not time, as most phase changes are, as there is no diffusion involved. Similarly, the austenite structure receives its name from steel alloys of a similar structure. It is the reversible diffusionless transition between these two phases that results in special properties. While martensite can be formed from austenite by rapidly cooling carbon-steel, this process is not reversible, so steel does not have shape-memory properties.

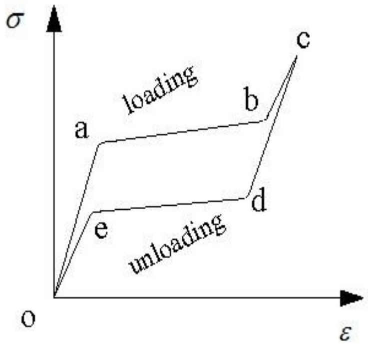

Figure 1. Superelasticity of SMAs

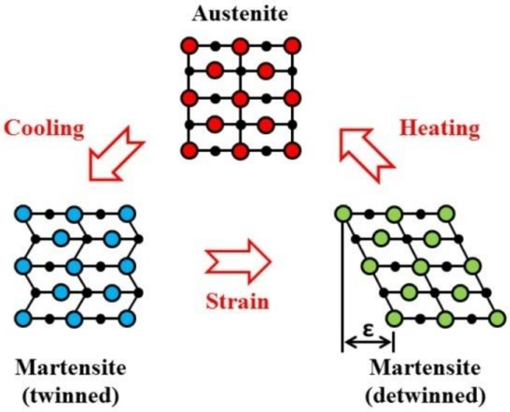

Figure 2. Microscopic phenomenology associated with the shape memory effect.

IV.1) ONE-WAY MEMORY EFFECT

When a shape-memory alloy is in its cold state (below A_s), the metal can be bent or stretched and will hold those shapes until heated above the transition temperature. Upon heating, the shape changes to its original. When the metal cools again, it will retain the shape, until deformed again.

With the one-way effect, cooling from high temperatures does not cause a macroscopic shape change. A deformation is necessary to create the low-temperature shape. On heating, transformation starts at A_s and is completed at A_f (typically 2 to 20 °C or hotter, depending on the alloy or the loading conditions). A_s is determined by the alloy type and composition and can vary between −150 °C and 200 °C.

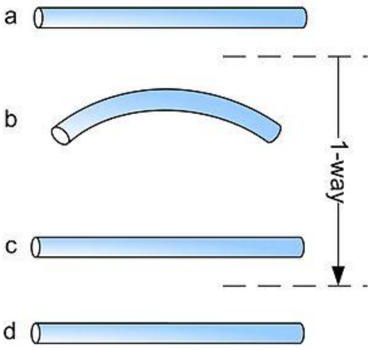

Figure 3. One way Memory effect

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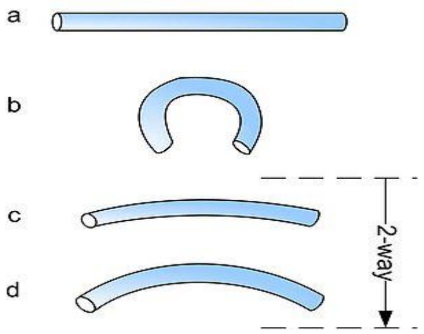

Figure 4. Two way Memory effect

IV.2) TWO-WAY MEMORY EFFECT

The two-way shape-memory effect is the effect that the material remembers two different shapes: one at low temperatures, and one at the high temperature. A material that shows a shape-memory effect during both heating and cooling is said to have two-way shape memory. This can also be obtained without the application of an external force (intrinsic two-way effect). The reason the material behaves so differently in these situations lies in training. Training implies that a shape memory can "learn" to behave in a certain way. Under normal circumstances, a shape-memory alloy "remembers" its low-temperature shape, but upon heating to recover the high-temperature shape, immediately "forgets" the low-temperature shape. However, it can be "trained" to "remember" to leave some reminders of the deformed low-temperature condition in the high-temperature phases. There are several ways of doing this. A shaped, trained object heated beyond a certain point will lose the two-way memory effect.

V. PSEUDOELASTICITY

The second property (pseudo-elasticity) of the martensitic transformation is related to the possibility of a phase transformation occurring by applying a suitable stress state under appropriate temperature conditions (T >Af). The alloy can reach the same highly deformable crystalline structure during the application of an external force, directly going from the austenite phase to the deformed martensite phase. During loading, the material gradually forms the martensite structure which instantly deforms, without permanently damaging the crystal structure. Compared to the previous case, there is no twinned martensite phase (the martensite generated due to temperature decrease). However, since the phase transformation occurs in a temperature range where the martensite phase is not stable (for T >Af the only stable phase is austenite), as soon as the external force is removed, the alloy reverts instantly to the parent phase, promoting an immediate shape recovery. The SMA immediately recovers its original shape and any large imposed deformation. Refer to figure 5 for details.

Both effects (SME and pseudo-elasticity) can be summarized in a single stress strain diagram, as shown in figure 6, although for different temperatures.

The pseudo-elastic effect can be observed for an SMA solid line. The SME is shown as a segmented line. Starting from a zero stress condition, the alloy is subjected to an applied stress. Initially the behaviour is linear due to elasticity in the100% austenite phase, with a Young's modulus equal to EA. 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). Initially the same linear behavior associated with elastic unloading of martensite is followed, until the austenite start stress (σAs) is reached.

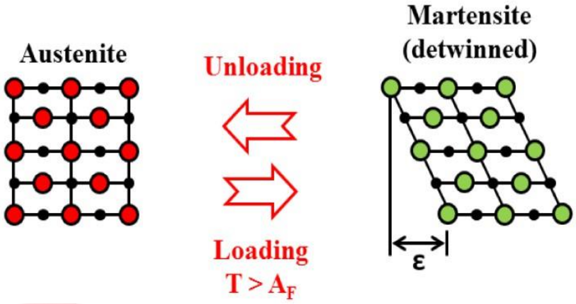

Figure 5. Microscopic phenomenology associated with the pseudo-elastic effect

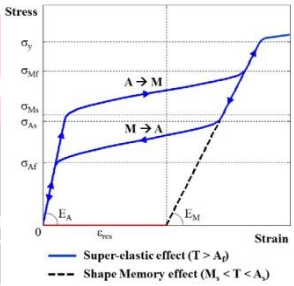

Figure 6. Typical SMA stress–strain diagram

VI. CRYSTAL STRUCTURES

Many metals have several different crystal structures at the same composition, but most metals do not show this shape-memory effect. The special property that allows shape-memory alloys to revert to their original shape after heating is that their crystal transformation is fully reversible. In most crystal transformations, the atoms in the structure will travel through the metal by diffusion, changing the composition locally, even though the metal as a whole is made of the same atoms. A reversible transformation does not involve this diffusion of atoms, instead all the atoms shift at the same time to form a new structure, much in the way a parallelogram can be made out of a square by pushing on two opposing sides. At different temperatures, different structures are preferred and when the structure is cooled through the transition temperature, the martensitic structure forms from the austenitic phase.

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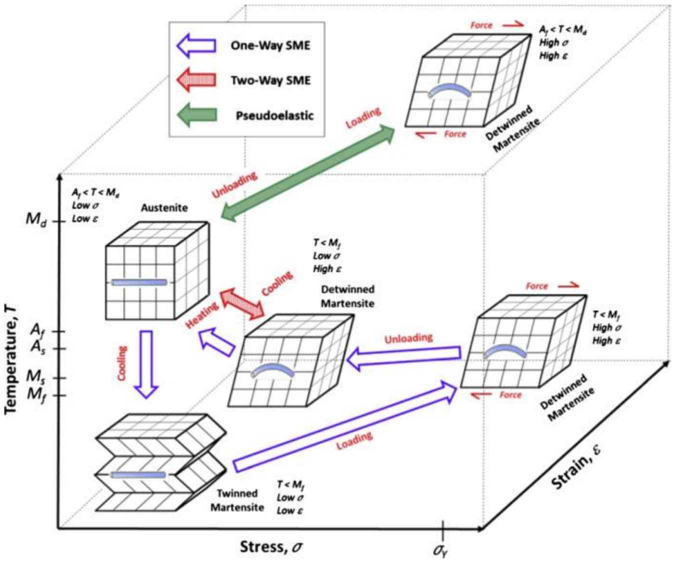
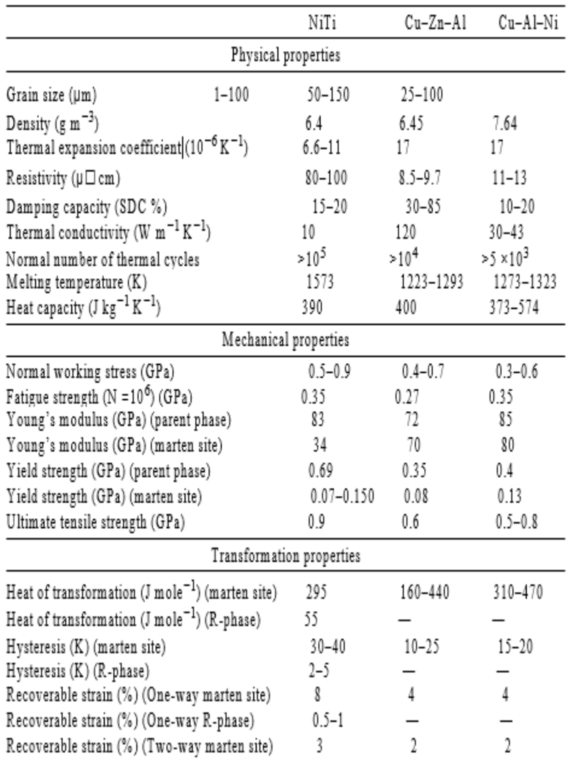


Figure 7. SMA Phases and Crystal Structures

VII. VARIABILITY OF SMA PROPERTIES

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 table.



	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 (μ□ 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) (marten site)	34	70	80
Yield strength (GPa) (parent phase)	0.69	0.35	0.4
Yield strength (GPa) (marten site)	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 ($J\ mole^{-1}$) (marten site)	295	160–440	310–470
Heat of transformation ($J\ mole^{-1}$) (R-phase)	55	—	—
Hysteresis (K) (marten site)	30–40	10–25	15–20
Hysteresis (K) (R-phase)	2–5	—	—
Recoverable strain (%) (One-way marten site)	8	4	4
Recoverable strain (%) (One-way R-phase)	0.5–1	—	—
Recoverable strain (%) (Two-way marten site)	3	2	2

Table 1. Variability of SMA properties with the pseudo-elastic effect

One of the main problems that may affect the mechanical and physical properties of SMAs is fatigue, particularly when exposed to overheating and overstressing over long periods of time. In general, the long-term performance and fatigue behavior of SMAs depend on the material processing (for instance,

fabrication process and heat treatment), the type of loading conditions (maximum temperature, stress, strain, environment, etc) and the transformation cycles achieved, among others. In most cases, SMA applications undergo a large number of transformation cycles by repeating a thermo- mechanical loading path, which may result in microstructural damage and, therefore, in low cycle fatigue (Kumar and Lagoudas 2008).

The fatigue behavior of SMAs can be induced by mechanically cycling the material between two stress or strain levels along a given loading path (Miller and Lagoudas 2000). In such a case, if the applied strain or stress level remains within the elastic regime, the fatigue life can be extended to as high as 10 million cycles (Kumar and Lagoudas 2008). On the contrary, if the SMA is cycled at high levels of load, through detwinning or stress-induced martensitic transformation, the fatigue life may be reduced to the order of thousands of cycles (Tobushi et al 1997).

The fatigue behavior of SMAs can also be produced by thermally-induced transformation cycles. On undergoing this type of thermal cycles, the fatigue behavior depends on the amount of transformation strain and stress level. A partial transformation may cause a significant extension of fatigue life (Miller and Lagoudas 2000, Bertacchini et al 2003). For instance, in wires of NiTiCu under a fixed stress level of 200 MPa, an extension of the fatigue life by a factor of approximately seven has been reported for a partial martensitic transformation (Kumar and Lagoudas 2008).Further investigations addressed the issue of fatigue in SMAs, and particularly of removal or reduction of its undesirable effects. Gall et al (2008) observed that the precipitate size and the crystallographic orientation in SMAs are also factors that may affect the fatigue life. These authors studied the fatigue performance of hot-rolled and cold-drawn NiTi bars. They obtained fatigue threshold values some five times smaller for the cold-drawn bars than the hot-rolled material. This difference was attributed to the significant residual stresses in the cold-drawn material, which amplify fatigue susceptibility despite superior measured monotonic properties.

VIII. STRUCTURAL FATIGUE AND FUNCTIONAL FATIGUE

SMA is subject to structural fatigue – a failure mode by which cyclic loading results in the initiation and propagation of a crack that eventually results in catastrophic loss of function by fracture. The physics behind this fatigue mode is accumulation of micro structural damage during cyclic loading. This failure mode is observed in most engineering materials, not just SMAs.

SMAs are also subject to functional fatigue, a failure mode not typical of most engineering materials, whereby the SMA does not fail structurally but loses its shape-memory/superelastic characteristics over time. As a result of cyclic loading (both mechanical and thermal), the material loses its ability to undergo a reversible phase

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transformation. For example, the working displacement in an actuator decreases with increasing cycle numbers. The physics behind this is gradual change in microstructure—more specifically, the build up of accommodation slip dislocations. This is often accompanied by a significant change in transformation temperatures. Design of SMA actuators may also influence both structural and functional fatigue of SMA, such as the pulley configurations in SMA-Pulley system.

IX. APPLICATIONS OF SHAPE MEMORY ALLOY

1) *Industrial*

a) Aircraft and spacecraft

Boeing, General Electric Aircraft Engines, Goodrich Corporation, NASA, Texas A&M University and All Nippon Airways developed the Variable Geometry Chevron using a NiTi SMA. Such a variable area fan nozzle (VAFN) design would allow for quieter and more efficient jet engines in the future. In 2005 and 2006, Boeing conducted successful flight testing of this technology.

SMAs are being explored as vibration dampers for launch vehicles and commercial jet engines. The large amount of hysteresis observed during the super elastic effect allow SMAs to dissipate energy and dampen vibrations. These materials show promise for reducing the high vibration loads on payloads during launch as well as on fan blades in commercial jet engines, allowing for more lightweight and efficient designs. SMAs also exhibit potential for other high shock applications such as ball bearings and landing gear.

There is also strong interest in using SMAs for a variety of actuator applications in commercial jet engines, which would significantly reduce their weight and boost efficiency. Further research needs to be conducted in this area, however, to increase the transformation temperatures and improve the mechanical properties of these materials before they can be successfully implemented. A review of recent advances in high-temperature shape-memory alloys (HTSMAs) is presented by Ma et al. A variety of wing-morphing technologies are also being explored.

b) Automotive

The first high-volume product (> 5Mio actuators / year) is an automotive valve used to control low pressure pneumatic bladders in a car seat that adjust the contour of the lumbar support / bolsters. The overall benefits of SMA over traditionally-used solenoids in this application (lower noise/EMC/weight/form factor/power consumption) were the crucial factor in the decision to replace the old standard technology with SMA.

The 2014 Chevrolet Corvette became the first vehicle to incorporate SMA actuators, which replaced heavier motorized actuators to open and close the hatch vent that releases air from the trunk, making it easier to close. 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.

c) Robotics

There have also been limited studies on using these materials in robotics, for example the hobbyist robot Stiquito as they make it possible to create very lightweight robots. Recently, a prosthetic hand was introduced by Loh et al. that can almost replicate the motions of a human hand.

2) *Bio-Engineered Robotic Hand*

There is some SMA-based prototypes of robotic hand that using shape memory effect (SME) to move fingers.

a) Civil structures

SMAs find a variety of applications in civil structures such as bridges and buildings. One such application is Intelligent Reinforced Concrete (IRC), which incorporates SMA wires embedded within the concrete. These wires can sense cracks and contract to heal micro-sized cracks. Another application is active tuning of structural natural frequency using SMA wires to dampen vibrations.

b) Piping

The first consumer commercial application was a shape-memory coupling for piping, e.g. oil pipe lines, for industrial applications, water pipes and similar types of piping for consumer/commercial applications.

c) Telecommunication

The second high volume application was an autofocus(AF) actuator for a smart phone. There are currently several companies working on an optical image stabilisation (OIS) module driven by wires made from SMAs.

3) *Medicine*

Shape-memory alloys are applied in medicine, for example, as fixation devices for osteotomies in orthopaedic surgery, as the actuator in surgical tools; active steerable surgical needles for minimally invasive percutaneous cancer interventions in the surgical procedures such as biopsy and brachytherapy in dental braces to exert constant tooth-moving forces on the teeth, in Capsule Endoscopy they can be used as a trigger for biopsy action.

The late 1980s saw the commercial introduction of Nitinol as an enabling technology in a number of minimally invasive endovascular medical applications. While more costly than stainless steel, the self expanding properties of Nitinol alloys manufactured to BTR (Body Temperature Response), have provided an attractive alternative to balloon expandable devices in stent grafts where it gives the ability to adapt to the shape of

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certain blood vessels when exposed to body temperature. On average, 50% of all peripheral vascular stents currently available on the worldwide market are manufactured with Nitinol.

a) Optometry

Eyeglass frames made from titanium-containing SMAs are marketed under the trademarks Flexon and TITAN flex. These frames are usually made out of shape-memory alloys that have their transition temperature set below the expected room temperature. This allows the frames to undergo large deformation under stress, yet regain their intended shape once the metal is unloaded again. The very large apparently elastic strains are due to the stress-induced martensitic effect, where the crystal structure can transform under loading, allowing the shape to change temporarily under load. This means that eyeglasses made of shape-memory alloys are more robust against being accidentally damaged.

b) Orthopedic surgery

Memory metal has been utilized in orthopedic surgery as a fixation-compression device for osteotomies, typically for lower extremity procedures. The device, usually in the form of a large staple, is stored in a refrigerator in its malleable form and is implanted into pre-drilled holes in the bone across an osteotomy. As the staple warms it returns to its non-malleable state and compresses the bony surfaces together to promote bone union.

c) Dentistry

The range of applications for SMAs has grown over the years, a major area of development being dentistry. One example is the prevalence of dental braces using SMA technology to exert constant tooth-moving forces on the teeth; the nitinol archwire was developed in 1972 by orthodontist George Andreasen. This revolutionized clinical orthodontics. Andreasen's alloy has a patterned shape memory, expanding and contracting within given temperature ranges because of its geometric programming.

Harmeet D. Walia later utilized the alloy in the manufacture of root canal files for endodontics.

d) Essential tremor

Traditional active cancellation techniques for tremor reduction use electrical, hydraulic, or pneumatic systems to actuate an object in the direction opposite to the disturbance. However, these systems are limited due to the large infrastructure required to produce large amplitudes of power at human tremor frequencies. SMAs have proven to be an effective method of actuation in hand-held applications, and have enabled a new class active tremor cancellation devices. One recent example of such device is the Liftware spoon, developed by Verily Life Sciences subsidiary Lift Labs.

4. *Engines*

Experimental solid state heat engines, operating from the relatively small temperature differences in cold and hot water reservoirs, have been developed since the 1970s, including the Banks Engine, developed by Ridgway Banks.

5. *Crafts*

Sold in small round lengths for use in affixment-free bracelets.

6. *Heating and cooling*

German scientists at Saarland University have produced a prototype machine that transfers heat using a nickel-titanium ("nitinol") alloy wire wrapped around a rotating cylinder. As the cylinder rotates, heat is absorbed on one side and released on the other, as the wire changes from its "superelastic" state to its unloaded state. According to a recent article released by Saarland University, the efficiency by which the heat is transferred appears to be higher than that of a typical heat pump or air conditioner.

Almost all air conditioners and heat pumps in use today employ vapor-compression of refrigerants. Over time, some of the refrigerants used in these systems leak into the atmosphere and contribute to global warming. If the new technology, which uses no refrigerants, proves economical and practical, it might offer a significant breakthrough in the effort to reduce climate change.

X. CONCLUSION

In this review, the main characteristics of shape memory alloys were discussed. It was discussed about the up gradation in Technology towards smart systems with adaptive or intelligent functions and features, which results in an undesirable increase in weight and volume of the associated machine components. SMAs are a unique class of metallic materials with the ability to recover their original shape at certain characteristic temperatures (shape memory effect) or to undergo large strains without plastic deformation or failure (super-elasticity). The Properties like One Way Memory Effect, Two Way Memory Effect and Pseudo elasticity were discussed. The Crystal structure of the SMA was reviewed and the properties of different SMAs were compared. The fatigue behavior of SMAs was also reviewed, along with some studies carried out to study fatigue life. The paper has also reviewed about the applications of SMAs in various fields viz; Industrial, Civil Structures, Medicine, Crafts, Engines and for Thermal processes.

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