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RESEARCH ARTICLE

FUTURE OF SHAPE MEMORY ALLOY AND ITS UTILIZATION

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ABSTRACT

A shape-memory alloy (also known as smart metal, memory metal, memory alloy, muscle wire, smart alloy) is an alloy that "remembers" its original shape and that when deformed returns to its pre-deformed shape when heated. This material is a lightweight, solid-state alternative to conventional actuators such as hydraulic, pneumatic, and motor-based systems. Shape-memory alloys have applications in industries including automotive, aerospace, biomedical and robotics. The two main types of shape-memory alloys are copper-aluminium-nickel, and nickel-titanium (NiTi) alloys 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, practicability (Wilkes, *et al*., 2000; Cederström and Van Humbeeck, 1995; Hodgson *et al*., 1990) and superior thermo-mechanic performance. (Huang, 2002) SMAs can exist in two different phases, with three different crystal structures (i.e. twinned martensite, detwinned martensite and austenite) and six possible transformations. (Sun and Huang, 2010; Mihálcz, 2001)

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INTRODUCTION

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 microstructural and functional properties of the material). (Shape Memory Materials, 1999) The maximum temperature at which SMAs can no longer be stress induced is called M_d, where the SMAs are permanently deformed. (Duerig and Pelton, 1994) 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. Nickel-titanium alloys have been found to be the most useful of all SMAs.

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Other shape memory alloys include copper-aluminum-nickel, copper-zinc-aluminum, and iron- manganese-silicon alloys. (Borden, 67) The generic name for the family of nickel-titanium alloys is Nitinol. In 1961, Nitinol, which stands for Nickel Titanium Naval Ordnance Laboratory, was discovered to possess the unique property of having shape memory. William J. Buehler, a researcher at the Naval Ordnance Laboratory in White Oak, Maryland, was the one to discover this shape memory alloy. The actual discovery of the shape memory property of Nitinol came about by accident. At a laboratory management meeting, a strip of Nitinol was presented that was bent out of shape many times. One of the people present, Dr. David S. Muzzey, heated it with his pipe lighter, and surprisingly, the strip stretched back to its original form.

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 remain in the hot 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.

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 shape. 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. Undernormalcircumstances,ashape-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. (Shape Memory Alloy Shape Training Tutorial, 2011) A shaped, trained object heated beyond a certain point will lose the two-way memory effect. There is another type of SMA, called a ferromagnetic shape-memory alloy (FSMA), that changes shape under strong magnetic fields. These materials are of particular interest as the magnetic response tends to be faster and more efficient than temperature-induced responses. Metal alloys are not the only thermally-responsive materials; shape-memory polymers have also been developed, and became commercially available in the late 1990s.

MATERIALS AND METHODS

Shape-memory alloys are typically made by casting, using vacuum arc melting or induction melting. These are specialist techniques used to keep impurities in the alloy to a minimum and ensure the metals are well mixed. The ingot is then hot rolled into longer sections and then drawn to turn it into wire. The way in which the alloys are "trained" depends on the properties wanted. The "training" dictates the shape that the alloy will remember when it is heated. This occurs by heating the alloy so that the dislocations re-order into stable positions, but not so hot that the material recrystallizes. They are heated to between 400 °C and 500 °C for 30 minutes, shaped while hot, and then are cooled rapidly by quenching in water or by cooling with air. There are various ways to manufacture Nitinol. Current techniques of producing nickel-titanium alloys include vacuum melting techniques such as electron-beam melting, vacuum arc melting or vacuum induction melting. "The cast ingot is press-forged and/or rotary forged prior to rod and wire rolling. Hot working to this point is done at temperatures between 700 ° C and 900 ° C" (Stoeckel and Yu, 3). There is also a process of cold working of Ni-Ti alloys. The procedure is similar to titanium wire fabrication. Carbide and diamond dies are used in the process to produce wires ranging from 0.075mm to 1.25mm in diameter. (Stoeckel and Yu, 4) Cold working of Nitinol causes "marked changes in the mechanical and physical properties of the alloy" (Jackson, Wagner, and Wasilewski, 21). These processes of the production of Nitinol are described in greater detail in Jackson, Wagner, and Wasilewski's report (15-22).

Properties

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. The properties of Nitinol are particular to the exact composition of the metal and the way it was processed. The physical properties of Nitinol include a melting point around 1240 ° C to 1310 ° C, and a density of around 6.5 g/cm³ (Jackson, Wagner, and Wasilewski, 23). Various other physical properties tested at different temperatures with various compositions of elements include electrical resitivity, thermoelectric power, Hall coefficient, velocity of sound, damping, heat capacity, magnetic susceptibility, and thermal conductivity (Jackson, Wagner, and Wasilewski, 23-55). Mechanical properties tested include hardness, impact toughness, fatigue strength, and machinability (Jackson, Wagner, and Wasilewski, 57-73). The large force generated upon returning to its original shape is a very useful property. Other useful properties of Nitinol are its "excellent damping characteristics at temperatures below the transition temperature range, its corrosion resistance, its nonmagnetic nature, its low density and its high fatigue strength" (Jackson, Wagner, and Wasilewski, 77). Nitinol is also to an extent impact- and heat-resistant (Kauffman and Mayo, 4). These properties translate into many uses for Nitinol.

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 microstructural 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 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 buildup of accommodation slip dislocations. This is often accompanied by a significant change in transformation temperatures. (Miyazaki *et al*., 2006)

Practical limitations

SMA have many advantages over traditional actuators, but do suffer from a series of limitations that may impede practical application.

Response time and response symmetry

SMA actuators are typically actuated electrically, where an electric current results in Joule heating. Deactivation typically occurs by free convective heat transfer to the ambient environment. Consequently, SMA actuation is typically asymmetric, with a relatively fast actuation time and a slow deactuation time. A number of methods have been proposed to reduce SMA deactivation time, including forced convection,[(15)] and lagging the SMA with a conductive material in order to manipulate the heat transfer rate. Novel methods to enhance the feasibility of SMA actuators include the use of a conductive "lagging". This method uses a thermal paste to rapidly transfer heat from the SMA by conduction. This heat is then more readily transferred to the environment by convection as the outer radii (and heat transfer area) is significantly greater than for the bare wire. This method results in a significant reduction in deactivation time and a symmetric activation profile. As a consequence of the increased heat transfer rate, the required current to achieve a given actuation force is increased. (Huang *et al*., 2012) Shape memory alloys (SMAs) are metals that "remember" their original shapes. SMAs are useful for such things as actuators which are materials that "change shape, stiffness, position, natural frequency, and other mechanical characteristics in response to temperature or electromagnetic fields" (Rogers, 155). The potential uses for SMAs especially as actuators have broadened the spectrum of many scientific fields. The study of the history and development of SMAs can provide an insight into a material involved in cutting-edge technology. The diverse applications for these metals have made them increasingly important and visible to the world.

Crystal Structures

Exactly what made these metals "remember" their original shapes was in question after the discovery of the shape-memory effect. Dr. Frederick E. Wang, an expert in crystal physics, pinpointed the structural changes at the atomic level which contributed to the unique properties these metals have.

He found that Nitinol had phase changes while still a solid. These phase changes, known as martensite and austenite, "involve the rearrangement of the position of particles within the crystal structure of the solid". Under the transition temperature, Nitinol is in the martensite phase. The transition temperature varies for different compositions from about -50 ° C to 166 °C. In the martensite phase, Nitinol can be bent into various shapes. To fix the "parent shape", the metal must be held in position and heated to about 500 °C. The high temperature "causes the atoms to arrange themselves into the most compact and regular pattern possible" resulting in a rigid cubic arrangement known as the austenite phase. Above the transition temperature, Nitinol reverts from the martensite to the austenite phase which changes it back into its parent shape. This cycle can be repeated millions of times.

Applications

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. (Mabe *et al*., 2008) 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. (Lagoudas and Hartl, 2007) SMAs also exhibit potential for other high shock applications such as ball bearings and landing gear. (DellaCorte, 2014) 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.[(22)] 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*. (Ma *et al*., 2010) A variety of wing-morphing technologies are also being explored. (Lagoudas and Hartl, 2007)

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.

Robotics: There have also been limited studies on using these materials in robotics, for example the hobbyist robot Stiquito (and "Roboterfrau Lara" (The Lara Project, 2011)), 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 (Loh2005). Other biomimetic applications are also being explored. Weak points of the technology are energy inefficiency, slow response times, and large hysteresis.

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 macro-sized cracks. Another application is active tuning of structural natural frequency using SMA wires to dampen vibrations. (Song *et al*., 2006)

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

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 stabilization (OIS) module driven by SMA wires.

Medicine: Shape-memory alloys are applied in medicine, for example, as fixation devices for osteotomies in orthopedic surgery, in dental braces to exert constant tooth-moving forces on the teeth. 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 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.

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.

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. (Mereau and Ford, 2006)

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. (Obituary, 2011) 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.

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.

Future Applications

Nitinol is being used in a variety of applications. They have been used for military, medical, safety, and robotics applications. The military has been using Nitinol couplers in F-14 fighter planes since the late 1960s. These couplers join hydraulic lines tightly and easily. (Kauffman and Mayo, 6) Many of the current applications of Nitinol have been in the field of medicine. Tweezers to remove foreign objects through small incisions were invented by NASA. Anchors with Nitinol hooks to attach tendons to bone were used for Orel Hershiser's shoulder surgery. Orthodontic wires made out of Nitinol reduces the need to retighten and adjust the wire. These wires also accelerate tooth motion as they revert to their original shapes. Nitinol eyeglass frames can be bent totally out of shape and return to their parent shape upon warming. (Kauffman and Mayo, 6) Nitinol needle wire localizers "used to locate and mark breast tumors so that subsequent surgery can be more exact and less invasive" utilize the metal's shape memory property. Another successful medical application is Nitinol's use as a guide for catheters through blood vessels (Stoeckel and Yu, 9-10).

There are examples of SMAs used in safety devices which will save lives in the future. Anti-scalding devices and fire-sprinklers utilizing SMAs are already on the market. The anti-scalding valves can be used in water faucets and shower heads. After a certain temperature, the device automatically shuts off the water flow. The main advantage of Nitinol-based fire sprinklers is the decrease in response time. Nitinol is being used in robotics actuators and micromanipulators to simulate human muscle motion. The main advantage of Nitinol is the smooth, controlled force it exerts upon activation. (Rogers, 156) Other miscellaneous applications of shape memory alloys include use in household appliances, in clothing, and in structures. A deep fryer utilizes the thermal sensitivity by lowering the basket into the oil at the correct temperature. (Falcioni, 114) According to Stoeckel and Yu, "one of the most unique and successful applications is the Ni-Ti underwire brassiere". These bras, which were engineered to be both comfortable and durable, are already extremely successful in Japan (Stoeckel and Yu, 11). Nitinol actuators as engine mounts and suspensions can also control vibration. These actuators can helpful prevent the destruction of such structures as buildings and bridges. (Rogers, 156)There are many possible applications for SMAs. Future applications are envisioned to include engines in cars and airplanes and electrical generators utilizing the mechanical energy resulting from the shape transformations. Nitinol with its shape memory property is also envisioned for use as car frames. Other possible automotive applications using SMA springs include engine cooling, carburetor and engine lubrication controls, and the control of a radiator blind ("to reduce the flow of air through the radiator at start-up when the engine is cold and hence to reduce fuel usage and exhaust emissions").SMAs are "ideally suited for use as fasteners, seals, connectors, and clamps" in a variety of applications (Borden, 67). Tighter connections and easier and more efficient installations result from the use of shape memory alloys (Borden, 72).

Conclusion

The many uses and applications of shape memory alloys ensure a bright future for these metals. Research is currently carried out at many robotics departments and materials science departments. With the innovative ideas for applications of SMAs and the number of products on the market using SMAs continually growing, advances in the field of shape memory alloys for use in many different fields of study seem very promising.

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