Shape memory alloys (SMAs) are a very promising class of metallic materials showing promising nonlinear properties, such as pseudo-elasticity behavior, shape memory effect and damping capacity, due to high mechanical hysteresis and internal friction. SMA have been recently applied in the field of neuromuscular rehabilitation, designing some new devices based on the above properties. The paper discusses possible uses of these materials in the treatment of movement disorders, such as dystonia or hyperkinesia, where their dynamic characteristics can be the key issue.

Key words: shape memory alloys, phase transformation, properties, pseudo-elasticity, neurology

INTRODUCTION

Shape memory alloys (SMAs) are unique materials since they can retain their original form, after being deformed by the application of heat above a certain temperature. Shape memory alloys are characterized by two stable crystallographic phases: austenite and martensite. Austenite is the high temperature phase and martensite is the low temperature one. During heating, the alloy changes from the martensite phase to the austenite phase, vice-versa on cooling. This feature of it and its superelasticity is what is used for all the application purposes.

The use of SMAs has increasingly expanded in recent decades [1-4]. Many researchers have intensively been involved in activities aimed at exploring innovative devices and applications, taking advantage of these smart materials. Indeed, the number of commercial applications is growing each year, with the largest application segment of the market represented by actuators and motors. The global market for smart materials was approximately \$19.6 \times 10^9 in 2010; it is estimated to \$80 \times 10^9 by the end of 2019, with an average annual growth rate of 7.8% between 2010 and 2019 [5].

The shape memory alloy’s market is not characterized by few active players in the world. The market players are mainly from Europe, Asia and the US. Growth driver for the shape memory alloy market is the advantage that it gives with respect to conventional systems that are setup in automotive and aerospace: due to its temperature sensitiveness, it does not need a whole system to behave like an actuator. It is resilient, wear resistant, temperature activated, bio-compatible, flexible and non-aggressive. Its replacement in place of the conventional actuators is advantageous as it reduces the weight of the body and it is cost effective. Since it is temperature activated, it also does not require any kind of secondary working system for the actuation.

SMAs show physical and mechanical features that made them successful candidates for use in structural engineering applications [6-9] and for nuclear applications [10]. Up to know, SMAs played a key role in the development and implementation of smart materials/devices, which can be integrated into structures to provide functions such as sensing, energy dissipation, actuation, monitoring, self-adapting, and healing of structures. In recent decades, intensive research efforts have been concentrated in the field of structural engineering, aiming at employing smart engineered systems in civil engineering applications, with emphasis to seismic response control of structures also in partial substitution of most commonly used steel materials [11-15]. Just as an example, several innovative systems and devices, mainly using NiTi and Cu-based SMAs, have been developed aimed to absorb a part of the seismic energy and reduce the earthquake forces acting on a structure, for damping control, structural retrofit, etc. SMAs have been integrated within these devices in many possible shapes and configurations, such as single and stranded wires, ribbons, strips, tubing, and bars.

Another major growth driver for the shape memory alloy has also been the boom in the medical sector and in general in the health sector, using shape memory alloy in dental, orthopedics, neural, vascular and surgical fields. This is mainly due to its good bio-compatibility, excellent magnetic resonance and Computer Tomography (CT) compatibility. This was also favored by an increasing use of Additive Manufacturing (3D printing) processes applied to metallic materials [16-17] with consequent customization of the component.
SMAs PHENOMENOLOGY

SMAs are a heterogeneous class of metal alloys. The main groups are ferromagnetic and non-ferromagnetic alloys, but only the non-ferromagnetic ones have practical applications. Among the non-ferromagnetic SMAs, two classes of compositions have been employed practically: Cu-based and NiTi-based, but the Ti ones are the most widespread due to their specific characteristics in most applications. Ni-Ti is a quasi-stoichiometric intermetallic compound with the predominant feature of undergoing an a-thermic reversible martensitic transformation between a cubic (B2) parent phase (austenite) and a monoclinic (B19') one (martensite). This phase transformation in the metallic lattice is at the base of interesting macroscopic effects, such as the Shape Memory Effect (SME) and Pseudo-Elasticity (PE). The direct B2–B19' transformation can be obtained by either cooling or introducing mechanical strains. Cooling the alloy in the B2 structure to a temperature lower than a characteristic point (M_s) induces exothermal formation of B19' in twinned ordering, without any macroscopic change in shape; on the other hand, subjecting B2 to strains in excess of approximately 1%–1.5% leads to a reversible movement of atomic layers and the formation of an un-twinned (or de-twinned) version of B19'. Conversely, starting with a martensitic structure, the heating up the alloy above a characteristic temperature (A_s) sets an endothermal transformation from B19' to B2; straining a twinned B19' structure produces a de-twinned B19'. For thermally-driven processes, transformations can be considered complete below M_s (direct transition B2–B19') and above A_s (reverse transition B19'–B2). In the mechanically-driven formation of de-twinned martensite, stress for initiating the process are proportional to the alloy temperature (Clausius–Clapeyron’s law). The precise values of characteristic temperatures M_s, M_f, A_s and A_f are functions of Ni content and depend, more subtly, on thermomechanical processing. Increases of one part in the thousands in Ni atomic concentration can produce drops by tens of degrees Kelvin in characteristic temperatures. Coming to the practical exploitation of these effects, because the de-twinning stress of initially twinned martensite is low compared to the de-twinning stress for the B2 phase (the latter is stable at higher temperature), NiTi is more deformable in martensitic state. By de-twinning B19', it is possible to obtain recoverable strains of up to 10%; recovery is achieved through heating above A_f, and the consequent reverse transformation to B2. This is called the SME. Thanks to SME, a weight heavy enough to induce B19' de-twinning at a temperature lower than M_s can be lifted during heating-induced strain recovery at a temperature appropriately higher than A_s. SME allowed a means of making solid-state actuators. PE is a different aspect of the same phenomenon. For alloys having an A_s lower than room temperature, the initial state before straining is B2. With a proper level of stress, de-twinned martensite can be formed in deformation. Strains up to 10% are readily recoverable upon removing the loading stress; being the working environment at a temperature higher than A_s, 12 is performed immediately. In this case, both the direct (loading) and inverse (unloading) transformations occur at constant stresses. The two plateaux are separated by mechanical hysteresis, and the area of the hysteresis loop corresponds to energy lost by structural viscosity in the process of loading and unloading. Fatigue life in SMA depends strongly on the levels of stress and maximal strains. Strains of 10% are incompatible with cyclic applications, for which 4% can be considered an upper limit, unless a high number of cycles is required, in which case, strains as low as maximum 1% or less would be appropriate, depending on stress.

NEURO-REHABILITATION APPLICATIONS: SOME RESULTS

Some applications of SMAs in the field of neuromuscular rehabilitation are reported and described, aimed to show the feasibility and relevant outcomes, and showing how the different functionalities of this class of materials can be applied.

Portable Devices for Passive and Aided Exercise

The physical rehabilitation of patients that suffer from paresis because of a neurological insult generally includes active exercise, which is often segmental at an initial stage and becomes increasingly functional as motor recovery proceeds. Although it is recognized that active exercise is extremely important for the re-acquisition of motor skills, passive mobilization of the limbs is also a standard part of physical treatment, because it can help safeguard the viscoelastic properties of tissues in other-
Compliant orthoses for limb repositioning

Spastic syndromes, are characterized by paresis, stiffness, involuntary phasic contractions and jerks of the limbs and, depending on the affected joint, unnatural flexion or extension. Immobility and disuse of the affected joints tend to have adverse consequences in that holding a static position for a long time can determine a shortening of the muscles and a worsening of contractures and spastic reflexes [22]. Orthoses can be used to stretch muscles affected by these malformations to restore a more physiological neutral posture and increase usable joint range of motion. In the practice of standard orthotic devices, a set of hinges has been recently reported [23] that provide a capital letter omega (Ω). This specific shape allows the material to be loaded along its entire length, precluding stress-related failures. The spring action is based on pseudo-elasticity.

Dynamic Applications and Movement Disorders

Some issues may arise with the use of wearable devices in the rehabilitation of neuromuscular diseases that have truly dynamic features. For instance, patients whose lower extremities are affected and have a residual capa-
The responsible for English language is: Elisabetta Petricci, Terni, Italy