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An innovative building envelope (kinetic façade) with Shape Memory Alloys used as actuators and sensors

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ABSTRACT

A panel actuated by a Shape Memory Alloys (SMA) wire is proposed for building envelopes, in particular ventilated façades, and is aimed at improving architectural and energetic performances of buildings. The SMA is used with two purposes: energy-free thermal sensors (not requiring electric current or other energy sources to be activated), and actuators where the movement is due to the large amount of energy produced by phase changing associated with thermal variations. During summer, façade panels open to allow natural ventilation in the cavity in between the external façade and the internal wall, while during winter panels close for building thermal insulation, provided by the still air in the cavity. We investigate the theoretical background behind the panel idea, and then we develop a prototype where its practical feasibility is shown. The material is Aluminum for the panel and Nitinol (Ni-Ti) for the wire providing the necessary force to open the panel. The final aim is the achievement of a sustainable façade that reacts to thermal variations without energy supply.

1. Introduction

The building skin plays a very important role as interface between the environment in which it is inserted and the interior users. Recently, the design of exterior surfaces of buildings is achieving a strategic role, to meet more and more complex requirements, and to reach ambitious objectives that range through communication, pure experimentation, environmental integration, to energy saving [1]. Building façades are the place for new experiments with increasingly innovative systems and technologies, like for example the "double-skin" facades [2], which consist of three different parts (outer layer, cavity and inner layer), where the cavity is used for thermal insulation in winter (still air) and natural ventilation in summer. Another important field concerns "Phase change materials" (PCM) [3–4], which are used on building envelopes to provide energy savings by using the material's features to change its internal structure with temperature variations. Today these are the most investigated fields, but in recent applications on facades other smart materials are used, as well as new technologies that allow the achievement of moving surfaces that interact visually and physically with the environment, and which are called "kinetic facades" [5]. A kinetic façade is designed so that it, or its main part, can move, while preserving the whole structural integrity.

The mobility of a façade could have a purely expressive and formal function [6–7] (for example, the movements may return the feeling of a "breathing" building), or it may be able to respond to environmental conditions and perform functions that would not be possible for a static structure; we mention, for example the dynamic solar shielding [8], where the controlling functions are driven electrically. They are often used to control the amount of heat admitted to a building, so that they can reduce the building energy request both for winter heating and summer cooling. Today there is a wide range of solar shading products on the market; the most used are sun awnings, roller shutters, vertical roller blinds, coated glass slats, horizontal and vertical solar fins, louvers, etc.

Within the previous framework, this work is devoted to the development of a new concept of kinetic façades, where the moving objects are façade panels, and the force needed to move the single panel is provided by Shape Memory Alloy (SMA) [9–10] wires. In fact, the use of SMAs permits us to supply buildings with new features that they do not have naturally. In particular, the movement happens *without* external energy consumption [2–4,8], a fact that is particularly worthy in our age where the energy saving becomes strategic. The proposed envelope is thought to be applicable to existing buildings to give them a new architectural identity (abandoned or degraded buildings, without formal or functional qualities), and to improve their energetic features. This façade technology can also be applied in the design of new buildings, in which it will be integrated with other components.

When the SMA detects a "summer" temperature, which has been tuned to 30 °C in this work, the shape recovery will allow panels to open and, when the temperature decreases below the "winter"

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temperature, which has been tuned to 20 °C, the panel closes using its own rigidity, without using electrical energy.

During summer, the panel opening will cause enhanced cavity ventilation, and so an improvement of the "chimney effect" [11] which makes the internal part of the building more comfortable. This effect is wind and building orientation independent, and it is caused by the density difference between hot and cold air. The first has a lower density than the second, thus the hot air flows up and leaves the façade cavity, while cold air comes in from bottom.

To have a good air change rate of the ventilated façade, there are three design parameters to consider, namely the temperature gradient between internal and external ambient, the air grids dimension, and their vertical distance. With the proposed device, the panel is curved toward the outside of an amount necessary to guarantee the right air flux entry; in particular, the distance between the structural frame and the maximum panel opening is to be determined in order to have neither load losses nor speed decrease, or by trying to make them negligible. Unlike common ventilated façades, this system operates without the need of air grids for the flux regulation; their use is restricted to particular cases only [11]. We can also guard from unexpected temperature variations, for example storms and particular cold winds; we can further respond promptly to those days in which the temperature is not in seasonal values (e.g., 30 °C in October).

The performances are guaranteed by SMA thermo-mechanical properties, and no power supply is required. This makes the proposed façade completely sustainable and reliable, as no frequent maintenance is required.

In this work, the main application is ventilated façades, and thus the improvement of thermal comfort in buildings. We are still at the "proof of concept" stage, as further developments are certainly needed to optimize the product. However, other applications can be foreseen, such as fire prevention, integration with other materials, etc. They are also left for future developments.

2. Shape Memory Alloys

Before explaining the proposed panel for kinetic façades, we found it useful to summarize the main properties of SMAs and how the Shape Memory effect works, which has been found in many types of alloys: Ni-Ti, CuAlNi, CuZnAl, AuCd, FeMn, etc. Ni-Ti (also known as "Nitinol") is the most used (and likely the most famous) because of its corrosion resistance, ductility, high deformation recovery and biocompatibility properties.

A SMA is a metallic material that has the ability to recover a given shape when subjected to a suitable thermal cycle [12]. More precisely, the shape is fixed through a thermal treatment, then the alloy is cooled to relatively low temperatures and plastically deformed; when the alloy is heated it returns to the shape that it had before deformation. Alloys that show shape memory only by heating are called "one-way" [13], while alloys that show shape changing even after a further cooling are called "two-way" [14].

Regarding the thermal behavior, SMAs present, at cooling, a transformation from austenite (parent phase) to martensite (generated phase). Martensite transformation starts at temperature Ms and ends at a temperature Mf, while Austenite transformation starts at a temperature As and ends at a temperature Af. Temperatures Ms and Mf are lower than As and Af, and so we have only one hysteretic cycle, usually about 15–25°. A sketch of this behavior is depicted in Fig. 1, where also the characteristic hysteric loop is shown.

Start and end temperatures depend on the composition of the specific SMA and on previous thermal treatments [15–19]. Cooling transformation from austenite to martensite is reversible: during a subsequent heating, martensite transforms itself again in austenite.

The hysteresis shown in Fig. 1 depends on the characteristics of the considered alloy. Actually, even small variations in components ratios may have drastic effects on the temperatures that characterize the alloy phase transformation. This is at the origin of the most important engineering properties of these materials, namely their ability to be designed according to a given requirement.

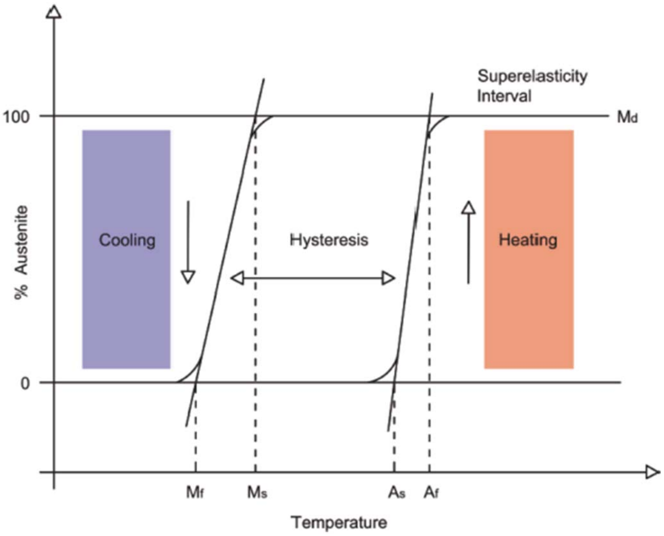

Fig. 1. A sketch of the behavior of SMA.

For what concerns the mechanical behavior, SMAs basically have three different stress-strain mechanical behaviors, that are shown in Fig. 2. They depend on the temperature in which they are used.

For temperatures below the transition temperature Ms (case T2 in Fig. 2) there is only martensite, and the material is easily deformable with low stress. Unloading produces a residual deformation, which can be recovered only by heating above Af, where the material transforms itself in austenite, recovering the memorized shape.

No shape recovery occurs in the austenitic phase for temperatures T > Md (case T1 in Fig. 2), where Md is the transition temperature between the pseudoelastic and the austenitic phases, which constitutes the higher limit for martensite formation. In this austenitic phase, the SMA has a classical plastic strain after reaching the yield threshold, and the stress-strain curve is the same of a normal metal.

If the temperature is in the range between Af and Md (case T3 in Fig. 2), we can observe the superelastic behavior [9,10,20], which is the most characteristic mechanical behavior of these material: under the action of stress, it assumes a deformed configuration, beyond the elastic limit, that can be restored (passing through an hysteretic cycle) by removing the stress. In fact, superelasticity is the shape memory material ability to store and totally recover big strains (up to 6–8%). This process is due to the fact that in this range of temperatures the presence of

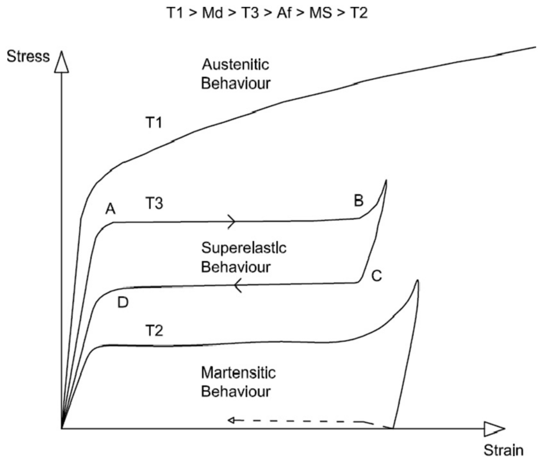

Fig. 2. Stress-strain curves of SMA at three different temperatures.