Study of an active deformable structure with embedded NiTi shape memory alloy strips

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The possibility of realising adaptive structures is of great interest in the control/automation fields, owing to the benefits related to enhanced performance. To accomplish this, a challenging approach is the employment of Shape Memory Alloys (SMAs) as active elements, which can recover seemingly permanent strains by temperature-induced phase transformations whereby the so-called Shape Memory Effect (SME) takes place. This paper deals with an experimental investigation of the bending recovery performance of a functional structure. The active material was a near-equiatomic NiTi alloy in the form of strips, which were embedded into a custom-made polymeric matrix. To study the influence of heating/cooling rates on the characteristic transformation temperatures of the NiTi material, several analyses were carried out by means of Differential Scanning Calorimetry (DSC). Prior to the insertion, the strips were thermo-mechanically treated to memorise a bent shape through experimentally evaluated shape setting parameters. The martensitic and reverse martensitic transformations were thermally activated by means of a hot/cold air stream flow. Experimental tests enabled the characterisation of the SME recovery behaviour evolution as well as the shape changes of the structure. Subsequently thermal activations were considered to assess the stability of the functional structure deformations (polymeric matrix with SMA strips) whose actual deflections were evaluated by means of digital image analysis.

Keywords: Shape memory alloys - Phase transformation - Thermo-mechanical treatments - Material characterisation

INTRODUCTION

Shape Memory Alloys (SMAs) are a unique class of metallic materials with the ability of memorising and recovering seemingly permanent strains by temperature and/or stress induced solid phase transformation between the two crystallographic phases: the cubic crystal structure (austenite, A) and the monoclinic crystal structure (martensite, M) [1, 2]. Thermoelastic martensitic transformation and related changes in the crystallographic lattice are responsible for the so-called Shape Memory Effect (SME), whereby the material can recover induced strains (up to 10 %) when it is deformed in the low temperature phase (M) and then heated to the high temperature phase (A). In the stress-free condition, the reverse transformation (martensite-to-austenite) occurs on heating. This begins at the austenitic start temperature A_s and ends at the austenitic finish temperature A_f while the forward transformation (austenite-to-martensite) occurs on cooling and begins at the martensitic start temperature M_s and ends at the martensitic finish temperature M_f.

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Over the last decades a wide variety of SMAs have been investigated and several alloy compositions have been studied, by adding elements such as Cu, Zn, Fe and Mn to existing alloys. Among the different types of SMAs employed for engineering applications, the near equiatomic NiTi alloys are the most widely-used owing to their superior shape-memory properties in comparison with other commercially available SMAs, thermal stability, narrow transformation hysteresis, high damping capacity, large recoverable strain and recovery stress and corrosion resistance [3]. Wires or strips are frequently used as active elements for the design of functional structures in which they are embedded in thermoplastic or thermosetting polymeric matrices to realise the so-called active deformable structures. The development of these advanced composites has gained large interest and increased application in several engineering approaches to smart systems [4]. This is mainly due to the ability of SMAs to sense thermal, mechanical, magnetic or electric stimuli, which achieve actuation or a pre-determined response. Thus, it is possible to tune static or dynamic features (shape, position, strain, stiffness, natural frequency) in response to environmental changes. SME is employed for active shape or stress control since shape changes may be induced by SME free strain recovery, whereas large stress may result from SME constrained strain recovery. In the latter condition phase transformation is associated with a high deformation capability, which leads to the generation of considerable stresses. As a result, SMAs allow the design of devices with reduced complexity, higher overall reliability, easier serviceability, cheaper implementation and a more compact arrangement in conjunction with improved lightness. The basic design of a functional structure, made up of SMA elements embedded in a polymeric matrix, can be summarised as a four-step route of the main input parameters: i) application requirements, ii) thermo-mechanical features of the alloy, iii) polymeric matrix properties and iv) functional structure behaviour. The first task is to identify which properties and performance are needed for the specific application. These factors, fundamental for the functional structure design and integration of SMA elements, are operating temperatures, operating loads and environmental features. Thermo-mechanical features of the alloy are also of great importance and should be evaluated according to the specific application constraint and requirements (displacement, force, actuator temperatures and actuating stimulus, SME stability and fatigue life) [5]. Furthermore, polymeric matrix properties are another crucial step since the material properties (glass-liquid transition temperature, elastic and flexural modulus) as well as the deformation abilities are fundamental to reach the maximum actuator strain. Finally, the functional structure behaviour has to be considered in order to realise a system with the desired response time and thermo-mechanical loading conditions as well as repeatable recovery ability on increasing actuation cycles.

In the present work the research activity is focused on the design and testing of a functional structure obtained by embedding near equiatomic NiTi strips in a polymeric matrix plate. Firstly, the polymeric structure design and the fabrication, by means of injection moulding technique, were considered. The bending deflection of the structure was activated by inducing the phase transformation of the SMA material, which was thermally activated by a hot/cold air stream flow. For this reason the strips were put in contact with the fluid through purpose-built slots. In an attempt to optimise the SME of the strips, a specific shape setting to memorise a bent shape was experimentally tuned by a specially designed thermo-mechanical treatment. A purpose-built wind tunnel enabled the testing of the functional structure (polymeric matrix equipped with SMA strips) with uniform thermal conditions of the air stream flow. On heating, the SMA materials tend to recover the memorised shape leading to the structure deflection whose recovery behaviour was evaluated by digital image analysis technique. Subsequently, to assess the morphing ability of the functional structure, thermal activations were carried out. Experimental tests showed the proficiency of the shape setting parameters and the SME stability with the increasing number of thermal cycles.

POLYMERIC STRUCTURE DESIGN

The first task was the functional structure design, performed with the aim of studying the recovery behaviour of the NiTi strips working in partially constrained conditions. The recovery stress due to the SMA phase transformation enables the production of significant shape changes in the polymeric host structure. The matrix was designed in order to be sufficiently compliant and flexible to support the deflections induced by the strips. Since the SMA phase transformation to induce the bending force on the polymeric structure was thermally activated by a hot/cold air stream flow, the strips were located into purpose-built slots in direct contact with the fluid flow. For the needs related to the designing and manufacturing features, a polymeric mixture of Nylon PA 6.6, glass fibre (15 %) and elastomer (5 %) was chosen to produce the structure by injection moulding technique.

SMA STRIP CHARACTERISATION

Commercially available NiTi shape memory alloy strips were considered to evaluate their bending ability. The choice of the SMA compound was guided by the need of having reverse transformation

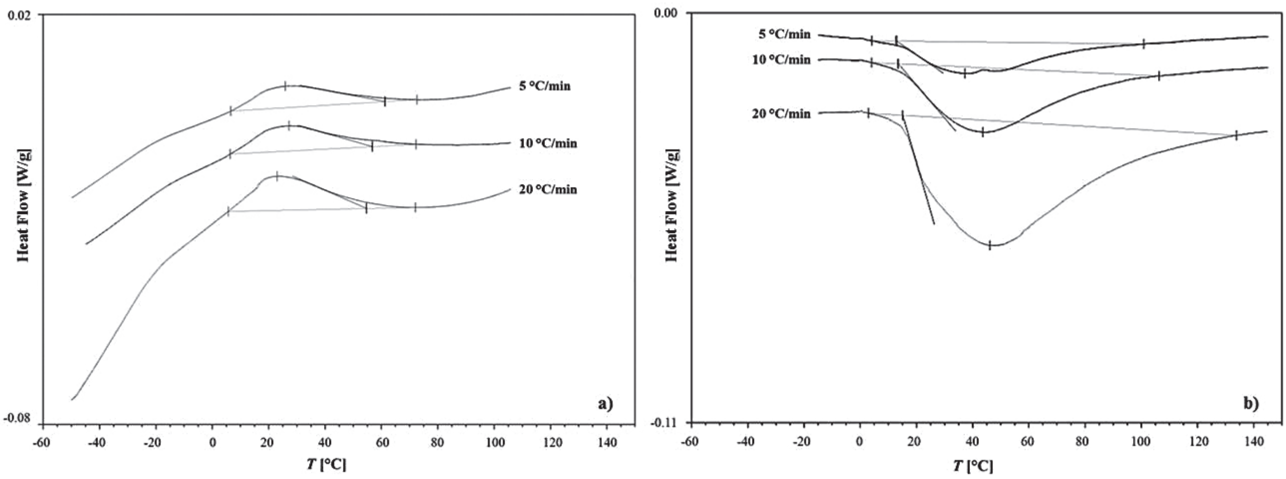

Fig. 1 – DSC thermograms at different heating/cooling rates: (a) exothermic peaks on cooling and (b) endothermic peaks on heating

Fig. 1 – Termogrammi DSC a differenti velocità di riscaldamento/raffreddamento: (a) picchi esotermici al raffreddamento e (b) picchi endotermici al riscaldamento

temperatures closest to those encountered by the functional structure during the operation. Starting from a 1.5 mm thick plane foil of material with a nominal composition of $Ti_{50.2}Ni_{49.8}$, the strips were cut by means of electro-erosion machining in order to minimise microstructural alterations resulting from thermo-mechanical stresses induced by cutting processes. Starting from the supplied foil the strips were cut to a dimension of 1.5 mm × 15 mm × 77 mm.

According to ASTM F2004 standard, Differential Scanning Calorimetry (DSC) tests were carried out on a small fraction of the untreated material to evaluate the zero-stress transformation temperatures. In an attempt to evaluate the influence of the heating/cooling rates during DSC tests on the TTRs [6, 7], the transformations were studied at 5 °C/min, 10 °C/min and 20 °C/min. Fig. 1a shows the exothermic peaks on cooling for the forward transformation while Fig. 1b shows the endothermic peaks on heating for the reverse transformation.

The characteristic martensitic and austenitic transformation temperatures (TTRs) were obtained from the DSC data through the tangential line method by the intersections between the baseline of the DSC curves and the tangents to the start and end regions of the transformation peaks [8]. The absorbed/released heat was calculated from the area under the curve of the heat flow between the start and finish temperatures of transformations. TTRs and latent heats per unit mass for both forward and reverse transformations are summarised in Tab. 1. The results showed that heating/cooling rates have the strongest

Heating/ cooling rate [°C/min]	A_s [°C]	A_f [°C]	ΔH_A [J/g]	M_s [°C]	M_f [°C]	ΔH_M [J/g]
5	11	86	4.6	62	6	1.1
10	10	90	4.9	64	6	1.2
20	12	110	5.9	58	5	0.8

Tab. 1 – Transformation temperatures and latent heats for both forward and reverse transformations at different heating/cooling rates

Tab. 1 – Temperature di trasformazione e calori latenti delle trasformazioni diretta e inversa a differenti velocità di riscaldamento/raffreddamento

influence on the A_f temperature which increased with increasing heating/cooling rates, ranging from 86 °C to 110 °C. Conversely, the austenite-to-martensite transformation temperatures and the reverse start transformation temperature were not so sensitive to the scanning rate.

According to these experimental findings, a specific shape setting thermo-mechanical treatment was developed. A representative scheme of the shape setting treatment is depicted in Fig. 2. The best thermo-mechanical treatment parameters (temperature, time and strain) to memorise the bent shape were experimentally achieved, starting from the best heat treatment parameters resulting from previous studies [9, 10], which suggested that heating the NiTi alloy in constrained conditions at 450 °C for 25 min allows 92 % of shape recovery.

In order to delete any residual stresses of previous

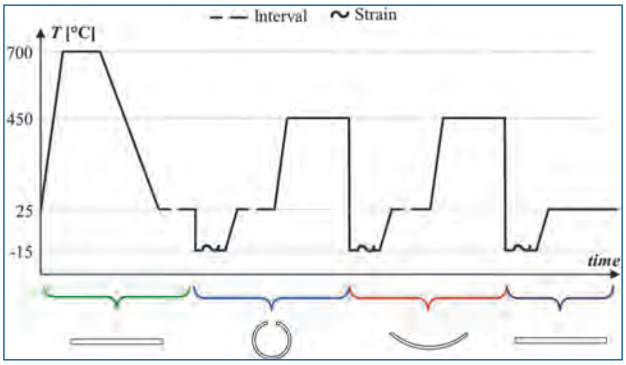

Fig. 2 – Representative scheme of the shape setting

Fig. 2 – Schema del trattamento di memorizzazione della forma

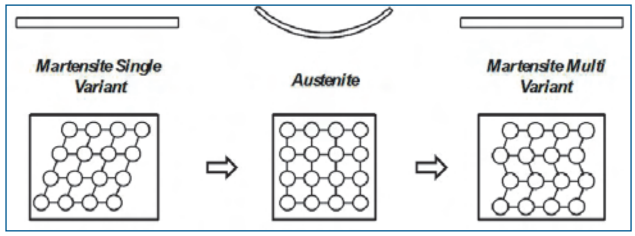

Fig. 3 –Diagram of the crystal lattice changes of the strips embedded in the functional structure

Fig. 3 – Schema delle trasformazioni cristalline delle lamine all'interno della struttura funzionale

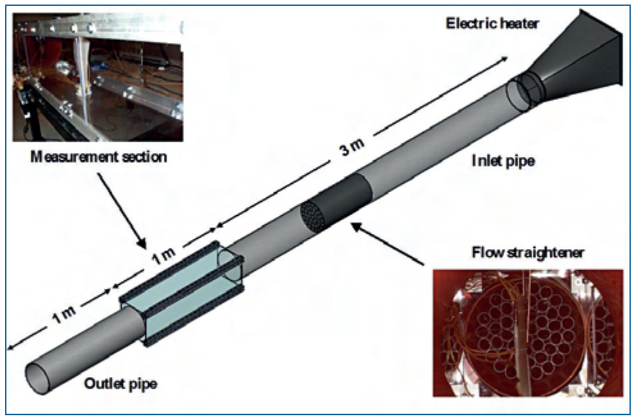

Fig. 4 – Functional diagram of the wind tunnel [11]

Fig. 4 – Schema funzionale della galleria del vento [11]

thermo-mechanical history, the strips were firstly annealed at 700 °C for 20 min and cooled to room temperature in calm air. In an attempt to maximise the deflection of the polymeric structure and based on the transformation temperature data resulting from DSC, the thermo-mechanical treatment was carried out according to the following steps. To memorise the desired bent shape a double thermo-mechanical treatment was performed. Firstly, the strips were pre-strained in the martensitic state, by immersion in a propylene glycol bath cooled to -15 °C (which is lower than M_f), and wound on a cylindrical jig to reach a circular shape. In order to avoid the shape recovery during the heating process, this set-up was placed into a tube furnace in constrained conditions to memorise the circular shape. The strips were then heated at 450 °C for 25 min and quenched in the propylene glycol bath cooled to -15 °C. After this first treatment, the strips were again put in the propylene glycol bath cooled to -15 °C and strained to be locked into a specifically designed arc clamp to reach an arc shape with a curvature radius of 42 mm. They were again thermally treated following the previous temperature and time conditions. Finally, the strips were strained in the martensitic state to perform the detwinning of the martensite and to reach the macroscopic flat shape for the embedding in the functional structure.
From a crystallographic point of view the crystal lattice changes of the embedded strips, related to the forward and reverse transformations, are depicted in Fig. 3. The strips, strained in the martensitic state, were mainly made up of single variant martensite (flat shape). On heating to a temperature above A_s the reverse phase transformation took place and led to the shape recovery of the SMA, which caused the deformation of the functional structure (arc shape). The subsequent cooling to a temperature below M_s allowed the formation of multi variant martensite and, thanks to the polymer elasticity, the macroscopic shape recovery was reached (flat shape).

EXPERIMENTAL SET-UP

For the activation tests a purpose-built wind tunnel was designed and realised. The functional scheme of the system with the main devices is reported in Fig. 4. The hot air stream flow is obtained by an electric heater and driven by an axial fan, which provide an air stream flow of about 8 m/s able to reproduce the actual operating temperature trend. By means of a convergent device the air flow is guided into the inlet pipe with a length of 3 m where the flow straightener allows a uniform and undisturbed flow field. The measurement section was built with PMMA transparent panels 1 m in length which ended in a circular pipe with a length of 1 m. Mineral insulated thermocouples type K were placed in correspondence to the heater, in the inlet and outlet of the

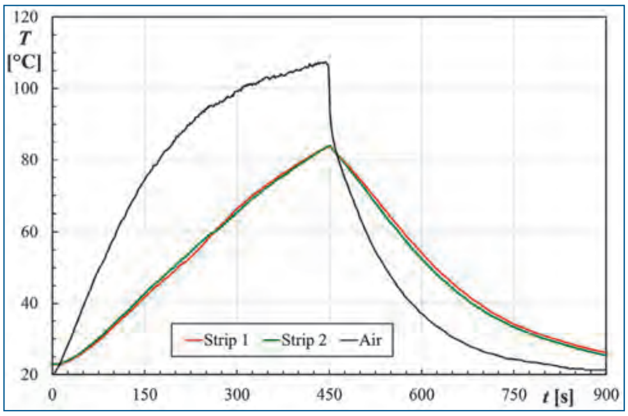

Fig. 5– Temperature trends for SMA strips and air temperature during thermal activation: heating and cooling ramps

Fig. 5 – Evoluzione delle temperature medie misurate sulle lamine e della temperatura del flusso d'aria durante l'attivazione termica: rampa di riscaldamento e rampa di raffreddamento

temperature the strips were heated by the hot air stream flow to reach an average value of 80 °C.

Subsequent to the heating, the system was cooled down to room temperature by the supplied air provided by the fan enabling the austenite-to-martensite phase transformation. As can be seen from the temperature-time trends reported in Fig. 5, the system enables an almost uniform thermal condition to be obtained on the strips during both the heating and the cooling ramps. On heating it was possible to reach 80 °C after 450 s, while on cooling the temperature reached 30 °C after 850 s. Moreover, the wind tunnel enabled a uniform thermal condition of the air flow stream.

RESULTS AND DISCUSSION

Thanks to the purpose-built wind tunnel described above, it was possible to test the recovery ability of the strips whose phase transformation allows the deflection of the structure. In Fig. 6 digital captures

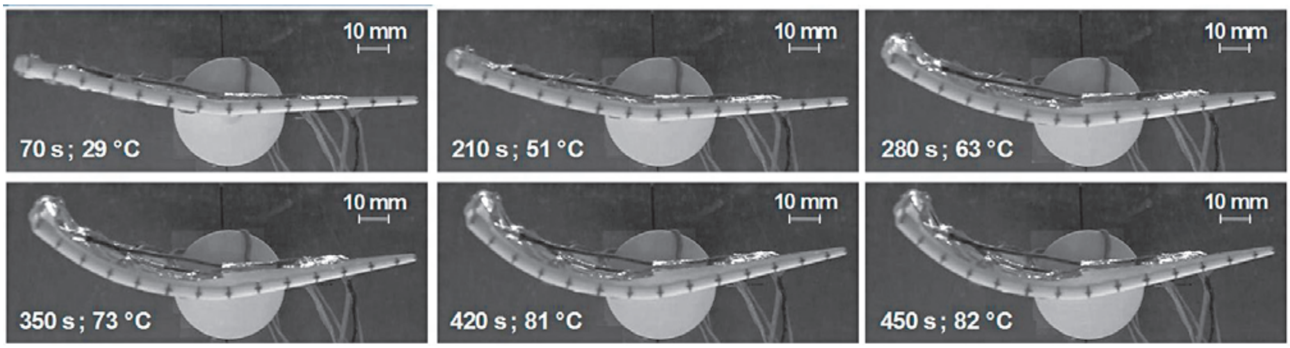

Fig. 6 – Digital captures from the recorded video: shape evolution during the heating ramp [11]

Fig. 6 – Immagini dell'acquisizione video: evoluzione della forma durante la rampa di riscaldamento [11]

measurement section to control and acquire the air temperature. Welded tip thermocouples type K were placed on the polymeric structure and on the SMA strips to evaluate the temperature evolution during the activation. Taking advantage of the transparency of the measurement section, the recovery behaviour of the structure was evaluated through digital camera video acquisition which was synchronized with the temperature evolution to link the shape evolution with the temperature changes. More details can be found in [11].

The thermal activation of the strips was achieved by a heating and a cooling ramp. Fig. 5 shows the experimental temperature evolution as a function of the time of the air temperature (black line) and of the average temperature on each strip (red and green lines), measured by the welded tip thermocouples put on both ends of the strips. Starting from room

from the recorded video, with the time instant and the value of the SMA strip surface temperature, are reported. As can be seen, during the heating ramp, as the temperature of all the SMA strips increased they tended to recover the memorised shape and the structure was forced to bend. As the fluid flow reached the maximum temperature the structure reached the maximum deflection and, in an attempt to recover the memorised arc shape, the strips caused the deflection of both ends of the structure.

To study the deformation achieved by the shape recovery of the SMA elements, the quantitative analysis of the deflections was carried out by digital image analysis techniques. From the digital captures, a CAD software reconstruction of the shape was performed taking advantage of the reference points drawn on the polymeric structure, through which it was possible to study the shape evolution. In

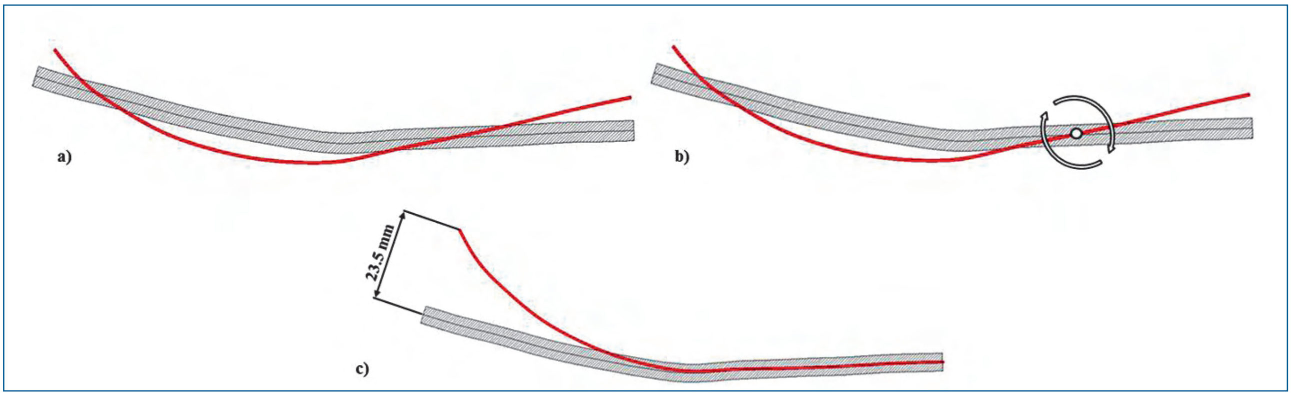

Fig. 7 – CAD software reconstruction: (a) comparison between non-activated condition (black background) and the centre line of the maximum deflection condition (red line); (b) deflection system measurement and (c) deflection measurement

Fig. 7 – Ricostruzione CAD: (a) confronto tra la condizione indeformata (campitura in nero) e linea media corrispondente alla massima deformata (linea rossa); (b) sistema di determinazione della massima deformata e (c) misura della freccia

Fig. 7 the reconstructed thickness of the structure divided by the centre line of the non-activated condition (black background) and the centre line of the maximum deflection condition (red line) are reported. To evaluate the actual deflection the right edge was aligned with the non-activated line, pivoting on the intersection between the centre line of the non-activated condition and the centre line of the maximum deflection condition (see Fig. 7b). The dimension of the deflection as measured in Fig. 7c was assumed as the maximum deformation provided.

The evolution of the SME of the strips on increasing activation cycles was considered performing 15 subsequent thermal activations. According to the CAD analysis previously described, it was possible to continuously evaluate the deflection on heating. The measurement of the deflections as a function of the SMA strips average temperature on heating, obtained for the first cycle analysis are reported in Fig. 8. Starting from the recorded video, digital captures were sampled at every 2 °C increase in the temperature of the strips, beginning from room temperature. Commencing from the non-activated condition, it is possible to observe the continuous and progressive structure deflection provided by the thermally activated phase transformation of the SMA strips. As the strips reached the maximum operating temperature (at about 80 °C), the structure reached its maximum level of deflection. However, given the steep ramp at 80 °C, if the temperature were increased further the level of deflection would also continue to increase.

The maximum deflection evolution with increasing thermal activation cycles is shown in Fig. 9. The reported trend suggests that the maximum deflection of the structure was achieved during the first activation cycle. The functional structure plate was shown to be capable of 23.5 mm displacement when activated. From the second cycle the deflection was likely to be around 7 mm with a 1 mm variation. The reported trend suggests that after the first cycle the polymeric structure was plastically deformed due to the strips action. Despite that, the structure deflection showed a reproducible behaviour with the increasing number of cycles.

CONCLUSIONS

In this paper, the development of a functional structure made up of a polymeric matrix with embedded SMA strips was proposed. The shape memory effect of the near-equiatomic NiTi strips was thermally activated by a hot/cold air stream flow. The thermal characterization of the SMA material enabled the study of the thermo-mechanical treatment for the shape setting whose parameters were experimentally tuned to maximise the shape memory effect in the NiTi strips. Experimental tests were performed by using a purpose-built wind tunnel which was enabled to achieve repeatable uniform thermal conditions of the air flow stream during the repeated tests. CAD software reconstructions allowed the quantitative evaluation of the functional structure deflection obtained by the solid phase transformation of the embedded strips. The results showed a continuous and progressive structure deflection according to the

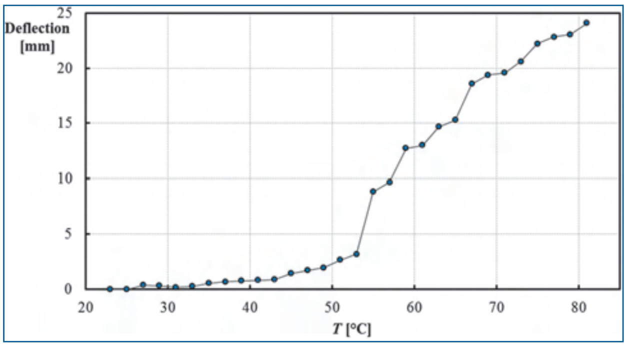

Fig. 8 – Deflection evolution as a function of the SMA strips average temperature on heating

Fig. 8 – Evoluzione della freccia in funzione della temperatura media misurata sulle lamine al riscaldamento

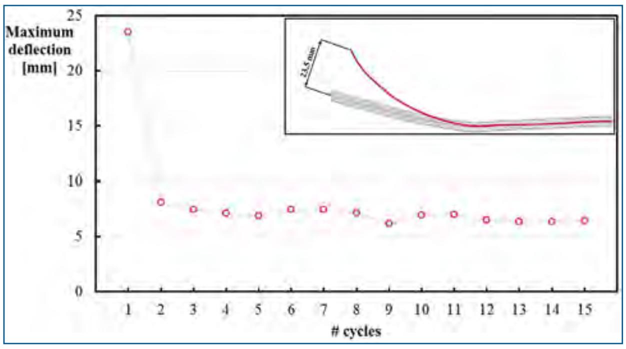

Fig. 9 – Maximum deflection evolution with increasing thermal activation cycles

Fig. 9 – Evoluzione della freccia massima in funzione del numero di cicli di attivazione termica

increasing of the air flow temperature. The functional structure was capable of a deflection of 23.5 mm when the strips reached the peak temperature (fully activated). Repeated activations highlighted the maximum deflection evolution with the increasing activation cycles: the first cycle showed the maximum deflection value, which caused a plastic deformation of the polymeric material. Despite that, from the second cycle the value was quite similar, indicating a reproducible behaviour of the functional structure. These preliminary results highlight the opportunity to take advantage of SMA strips as an effective active control of system actuation.

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Studio di una struttura attiva deformabile realizzata con lamine NiTi a memoria di forma

Parole chiave: Leghe a memoria di forma - Trasform. di fase - Proc. termomeccanici - Caratterizz. materiali

Nel lavoro sono presentati i risultati dell'attività sperimentale di caratterizzazione del comportamento funzionale di una lega a memoria di forma NiTi, sotto forma di lamine di dimensioni 1.5 mm × 15 mm × 77 mm, utilizzata come elemento attivo all'interno di una struttura attiva deformabile a matrice polimerica. Le leghe a memoria di forma sono caratterizzate dalla capacità di recuperare grandi deformazioni per effetto di trasformazioni di fase allo stato solido indotte da uno stimolo esterno, sia esso legato a temperatura, carico o campo magnetico applicato. La prima parte dell'attività ha riguardato la progettazione e realizzazione della struttura funzionale mediante stampaggio ad iniezione (PA 6.6 rinforzato al 15 % con fibre vetro e 5 % di elastomero). Tra le leghe a memoria di forma commercialmente disponibili è stata scelta la lega di composizione $Ti_{50.2}Ni_{49.8}$ le cui temperature di trasformazione fossero le più simili alle esigenze di esercizio. A partire dalle caratteristiche termiche del materiale e in relazione alle deformazioni flessionali richieste alla struttura polimerica, è stato quindi messo a punto un opportuno trattamento termomeccanico di memorizzazione della forma (Fig. 2). La trasformazione di fase responsabile del recupero della forma nelle lamine SMA è stata ottenuta mediante attivazione termica, operata da un flusso di aria generato all'interno di una galleria del vento appositamente progettata e realizzata (Fig. 4). In questo modo è stato possibile riprodurre le condizioni operative di funzionamento oltre che analizzare il gradiente termico nel polimero e nella lega NiTi. Le prove sperimentali di attivazione hanno permesso di studiare l'evoluzione del grado di recupero della forma e della conseguente deformazione a carico della struttura all'aumentare del numero di cicli di attivazione per effetto memoria. Mediante tecniche di analisi di immagine è stato possibile valutare quantitativamente la deformazione flessionale operata dalle lamine: all'aumentare della temperatura del flusso d'aria si assiste ad una deformazione continua e progressiva della freccia massima (Fig. 8). In corrispondenza del primo ciclo di attivazione si realizza il massimo valore della freccia pari a 23.5 mm; a partire dal secondo ciclo si assiste ad un progressivo effetto di stabilizzazione del comportamento.