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Influence of some extrinsic factors on the two way shape memory effect of electric actuators

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The paper analyses the reproducible behaviour of three work generating applications of shape memory electric actuators, trained for two way shape memory effect (TWSME) in bending. The first is a lifting device, the displacement-temperature variation of which is considered as a function of time while revealing the influence of applied load. The second is an electric circuit breaker (disjunctor) for electric overload protection, the functioning of which is compared to that of a bimetallic thermostat, while revealing the influence of applied voltage. The third is a composite with polymeric matrix, the geometrical evolutions of which are monitored as a function of temperature, while revealing the influence of matrix on the bending reproducible behaviour. A comparison is performed between the critical transformation temperatures of the three devices, by emphasizing the influence of extrinsic factors on their mechanical responses.

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Keywords: Cu-Zn-Al-Ni, Shape memory alloys, Actuator, Mechanical response, Critical temperatures, Reproducibility

1. Introduction

The three most successful applications of intelligent materials comprise: (i) sensors; (ii) actuators and (iii) control systems. They have been developed in accordance to animal organisms as replications of nerves, muscles and brain, respectively [1].

Actuators have been produced from various types of intelligent materials such as: piezoelectric, shape memory; electro and magnetostrictive and electro and magnetorheological materials [2].

The active elements of shape memory actuators can be made of alloys, ceramics and polymers. Among these categories, ceramic actuators provide the shortest response times, polymeric actuators provide the largest strokes yet shape memory alloys (SMAs) actuators are able to develop the largest forces. Besides larger forces SM electric actuators offer various other advantages, as compared to classical actuators, such as design simplicity, short response times and large developed strokes, providing a comprehensive collection of mechanical, hysteresis and temporal data is available [3]. Besides springs, that represent the most commonly used elements in SM actuators [4] other configurations have also been used among which wires [5], sliding plates with folded geometry [6] or even simpler shapes, as rods, sheets or lamellae [7]. Lamellar SM actuators, subjected to bending are the simplest elements able to develop work generating shape memory effect (SME) and to be trained for two way shape memory effect (TWSME) [8].

The present paper aims to reveal the influence that some extrinsic factors (applied load and voltage, nature and action mode of bias elements) have on the bending reproducible behaviour of Cu-Zn-Al-Ni shape memory electric actuators employed in three experimental setups: (1) a device for training-cycling in bending (deflectometer) that monitors load influence on displacement-temperature variation and achieves training [9]; (2) an electric circuit breaker (disjunctor) that interrupts the circuit when subjected to overheating voltages thus providing electric overload protection; (3) a polymer matrix-composite with active SM element, the TWSME of which is enhanced due to the contribution of matrix elasticity to cold shape resetting.

2. Experimental details

Lamellar specimens, were prepared from a Cu-21.64 Zn-7.14 Al -0.23 Ni (wt.%) SMA according to a previously detailed procedure [10]. Fig. 1 shows the DSC chart recorded at 10 ^oC/ min.

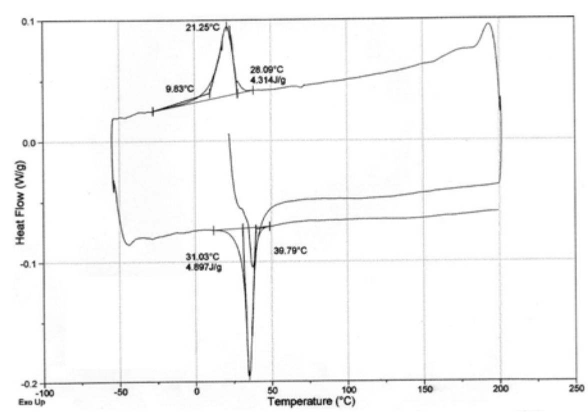

Fig. 1. DSC chart of a Cu-21.64 Zn-7.14 Al-0.23 Ni (wt.%) SMA in hot forged-hot rolled condition, recorded at 10^0K/ min.

Firstly the specimens were trained in bending, for TWSME on a special device (deflectometer) illustrated in Fig. 2. Training was accomplished during heating-cooling cycles applied to the specimens that had three different loads, of 0.24; 0.44 and 2.94 N, fastened to their free ends. The specimens were subjected to heating-cooling cycles during which they lifted the loads by shape memory effect (SME) and lowered them due to the softening induced by direct martensitic transformation.

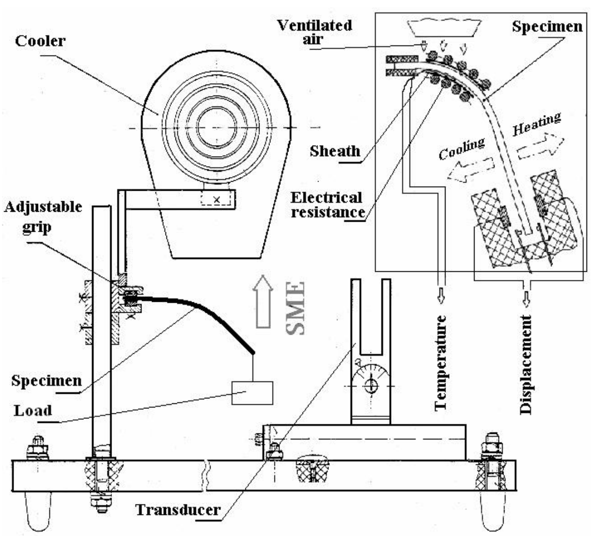

Fig. 2. Assembly of the training device in bending (deflectometer) with detail of the functioning principle.

After training, TWSME is obtained and the specimen performs the above motions in the absence of the load, at simple heat variation. The trained specimens were included in the structure of two devices: (1) an electric circuit breaker and (2) a polymer matrix-composite actuator.

The electric scheme of the electric circuit breaker (disjunctor) is shown in Fig. 3.

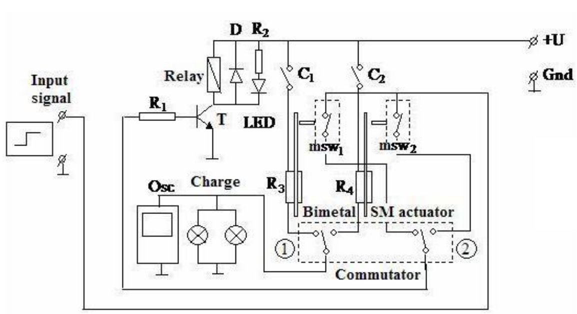

Fig. 3. Electric scheme of the installation for comparative testing of bimetals and shape memory lamellae: D - diode; $R_{1,2,3,4}$ - resistors; $C_{1,2}$ - electric contacts; Gnd – ground connection; T-transistor; $msw_{1,2}$ - microswitches; Osc – oscillator.

The input voltage has three values: 10; 12 and 14 V. The scheme comprises two distinct work channels that have in common the control block of the relay. In the case of the actuation of thermostatic bimetal, the microswitch msw_1 commands the transistor *T* through the resistor R_1. Then the contact C_1 closes the circuit and transfers the input voltage to the charge, consisting in 2 electric bulbs, connected in parallel to the ground, *Gnd*. The current passes through the resistor R_3 which heats up the bimetal, during the so called *pulse time*. The bimetal bends and pushes a rod that opens the microswitch msw_1 and cuts the supply to the electric charge. During the *break time* the bimetal cools down and bends to the opposite direction, finally closing again the microswitch msw_1. Thus, the succession of the pulse-break periods is resumed. Similarly, in the case of the of SM actuator, which was previously trained for TWSME in bending, the device works according to the same principle, the disconnection-connection of the microswitch msw_2 being commanded by TWSME.

The second actuation device is a composite obtained by embedding the trained SM lamellae, in cold shape, into polyuretane-polysiloxane copolymer or pure polysiloxane polymer matrixes. The consolidation of the former involves slight heating while the latter hardens at room temperature. The SMA/ polysiloxane composite actuator is shown in Fig. 4.

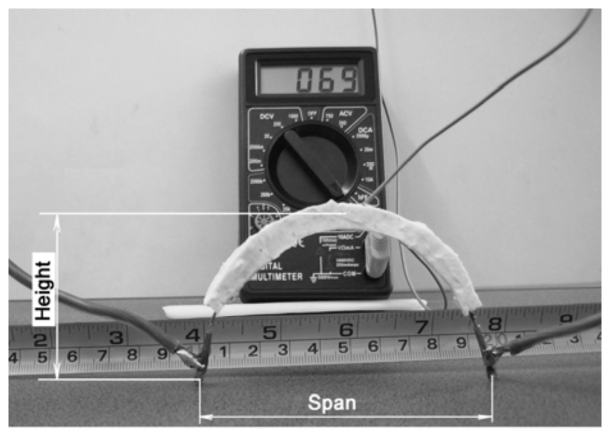

Fig. 4. Experimental setup for testing the variation with temperature of the span and height of the polymer matrix composite with SMA active elements.

During heating the SM lamella tends to straighten in such a way that the span increases and the height decreases. During cooling, the two dimensions vary in the opposite way. The behaviour of the composite was filmed and the variations of the span and height were determined by cinematographic analysis.

3. Experimental results and discussion

Owing to thermal inertia of the insulating sheath, the specimen's temperature raised with approx. 5 K even after heating was stopped and the cooler was switched on. In this way, a delay occurred between the variations in time of the temperature and the displacement. Their evolutions were illustrated in Fig. 5(a) and (b), for the first 5 thermal cycles, in the case wax paper sheath was used. C_i and H_i designate the triggering moments of cooling and heating, respectively in the cycle i. The average variation rates of temperature were 3.3 ^oC/sec for heating and 4.5 ^oC /sec for cooling, while the average variation rates of displacement were 0.27 mm/sec and 0.37 mm/sec, respectively.

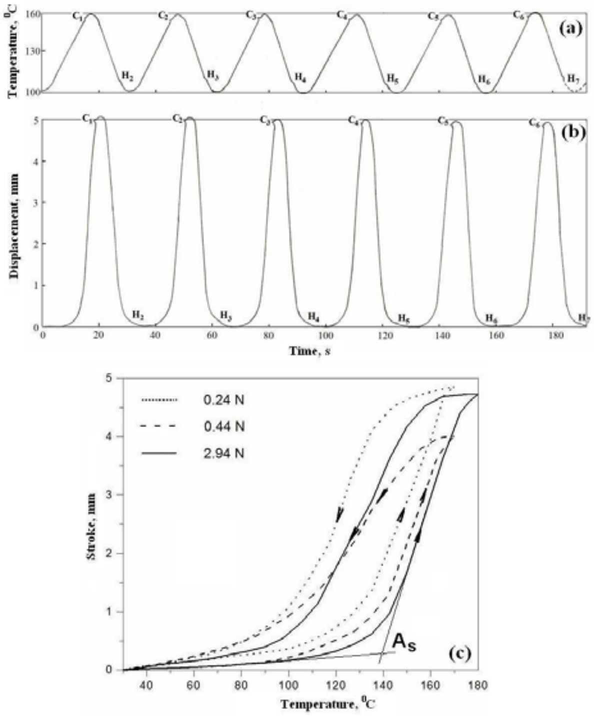

Fig. 5 Deflectometer characteristics during thermal cycling of a Cu-21.64 Zn-7.14 Al-0.23 Ni (wt.%) SMA actuator : (a) temperature variation in time for wax paper sheath; (b) displacement variation in time for wax paper sheath; (c) influence of the applied load on the stroke variation with temperature, for Teflon sheath.

This means that both temperature and displacement variation rates were lower with approx. 27 % during heating than during cooling. This difference could be caused by the lack of flexibility of wax paper sheath that accelerates deflection, acting as a bias spring for cold shape recovery and impedes displacement, causing a slight decrease of the stroke, after 5 cycles, as shown in Fig. 5(b).

On the other hand, the Teflon sheath, made from fine mesh fabric, is more flexible and has higher thermal conductivity as compared to wax paper. For this reason, the displacement-temperature variations illustrated in Fig. 5(c) became fairly reproducible, after 5 training cycles and no decreasing tendencies were noticeable.

As previously pointed out [11], in the case of the specimen trained in bending with a 2.94 N load fastened at its free end, the critical temperature (graphically determined as illustrated in Fig. 5) decreased after 1000 heating-cooling cycles from 137 ^oC to 132 ^oC.

After being trained in bending with an applied load of 2.94 N, SMA specimens were tested on the disjunctor, in parallel with a bimetal.

The commutation curves of both bimetal and SM actuator, with details of an impulse at the applied voltage of 14 V, are illustrated in Fig. 6, for the three applied voltages. Fig. 6(a) corresponds to the bimetallic thermostat and 6(b) to the SMA. It is noticeable that the SM actuator caused shorter pulse and break times. In addition, the detail from Fig. 6(a) shows a gradual triggering of the pulse, for the bimetal, which is inexistent in the detail from Fig. 6(b) corresponding to the SM actuator.

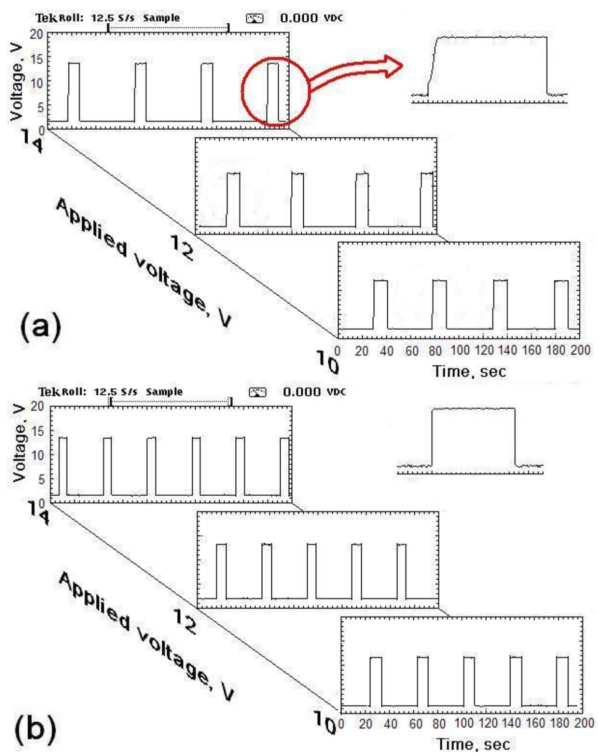

Fig. 6. Commutation curves of the disjunctor with details of an impulse, at three input applied voltages: (a) for bimetal; (b) for Cu-21.64 Zn-7.14 Al-0.23 Ni (wt.%) SM actuator.

A review of the average values of pulse and break periods, as a function of the applied voltage, is shown in Fig. 7.

Fig. 7(a) confirms the fact that pulse times were always shorter for SM actuator as compared to bimetal. The difference between the two pulse periods ranges between 2.3 – 2.8 sec and seems to be unaffected by the applied voltage. In the case of SM actuator the variation tendency of pulse period with voltage is almost linear.

In Fig. 7(b) break periods are also shorter for SM actuator and seem to be less sensible to applied voltage. Here the difference between the two break periods increases with the applied voltage, from less than 10 sec to over 20 sec. In both cases pulse (break) time variation with applied voltage was fairly linear in the case of the SM actuator.

The evolutions of the geometrical characteristics of the SMA/ polymer composite actuator are summarized in

Figs. 8 and 9, where a fourth degree polynomial fit was used. It is noticeable that between span variations, in Fig. 8(a) and (b) and height variations, in Fig. 9(c) and (d) the deviations of graphically determined critical transformations temperatures ranged within approximately 1 ^{o}C for heating and 2.4 ^{o}C for cooling.

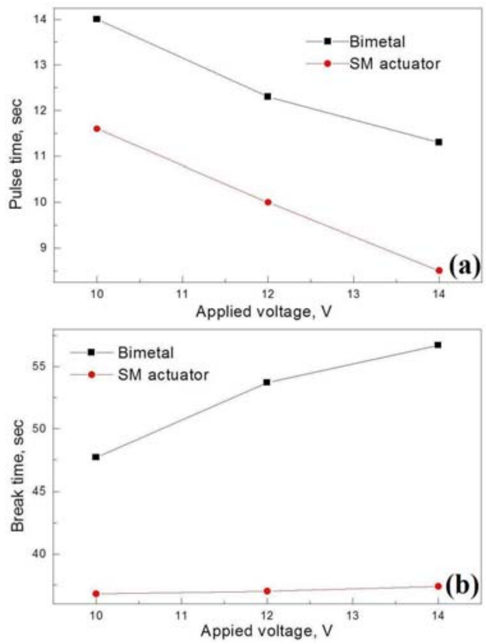

Fig. 7. Comparison between the functioning characteristics of a thermostatic bimetal and a Cu-21.64 Zn-7.14 Al-0.23 Ni (wt.%) SM actuator, determined from Fig.6: (a) pulse period; (b) break period.

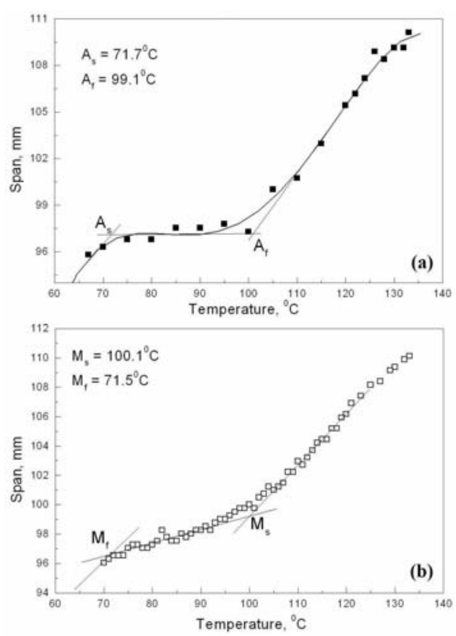

Fig. 8. Spam variations with temperature determined by cinematographic analysis: (a) spam variation during resistive heating; (b) spam variation during air cooling.

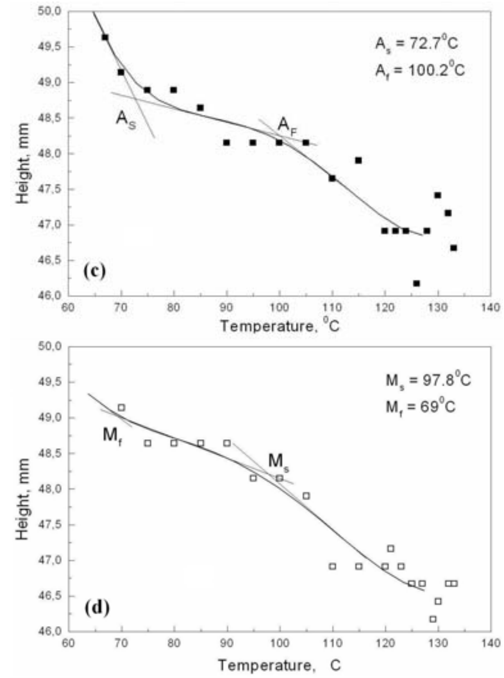

Fig. 9. Height variation with temperature determined by cinematographic analysis: (a) height variation during resistive heating; (b) height variation during air cooling.

The evolutions shown in Figs.8 and 9 were reproducible for tens of cycles, without any sign of degradation.

A summary of the values of critical transformation temperatures, as graphically determined above, is given in Table 1.

Table 1. Influence of extrinsic factors on the graphically determined values of critical transformation temperatures.

	M_f, ^{0}C	A_s, ^{0}C	M_s, ^{0}C	A_f, ^{0}C	Obs.
Free state	9.83	31.03	28.09	39.79	Fig. 1
Composite	69-71.5	71.7-72.7	97.8-100.1	99.1-100.2	Figs. 8,9
Trained in bending under 2.94 N	103	138	~ 156	~ 170	Fig. 5

Obviously the critical temperatures were the highest in Fig. 5 and the lowest in Fig. 1.

These differences could be fairly ascribed to the variation of temperature with stress, according to Clausius-Clapeyron equation, as it has been previously pointed out in the case of the actuators made from helical lamellar springs [12].

The lowest critical temperatures correspond to free state SMA, as determined by means of DSC. In free state, the material is undeformed, therefore the reversible martensitic transformation is pure.

The medium values correspond to the composite, which has a rather soft polymer matrix. While developing TWSME in embedment form, the trained specimens were subjected to lower and more uniformly distributed loads, as compared to that applied during training. Since it had to overcome a diminished load, the specimens transformed to lower critical temperatures, in agreement with Clausius-Clapeyron equation.

The largest critical temperatures values were obtained for the specimen trained in bending under an 2.94 N applied load.

5. Conclusions

The bending behaviour accompanying the occurrence of two way shape memory effect in a Cu-21.64 Zn-7.14 Al-0.23 Ni SMA was reported under the influence of three extrinsic factors:

(i) applied load, which was increased up to 2.94 N on a deflectometer;

(ii) applied voltage, which was increased up to 14 V on a disjunctor:

(iii) embedment form within a SMA/ polymer composite.

The critical transformation temperatures increased in the order 1. free state (pure transformation on DSC) $\Rightarrow$ 2. composite (polymer matrix) $\Rightarrow$ 3. deflectometer (2.94 N applied load).

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