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ADVANCED SHAPE MEMORY ELEMENTS FOR AUTOMOTIVE INDUSTRY

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Abstract: Shape memory alloys are metallic materials with unique special properties with applications in many different fields. In the automotive industry intelligent materials like SMAs can be used as thermal actuators for radiators shutters, fan clutches, fuel management, climate control, engine control, brake ventilation, transmission control or rattling noise reduction. In this paper we analyze, describe and conclude on few practical applications of SMAs in automobiles in order to improve them functionality or to propose new viable solutions. In this study a copper-based shape memory alloy was investigated as potential active element for a standard automotive thermostat. Twelve alloys were obtained with different transformation temperatures range in order to fulfill the practical requirements from local automotive industry.

Key words: shape memory alloy, automotive thermostat, cooling time.

1. INTRODUCTION

Nowadays in new - modern vehicles, especially passenger cars, the number of sensors and actuators are increasing tremendously due to the demand for safer and more comfortable vehicle. The emerging drive by wire technology, offers a wide range of opportunities for SMA actuators as an alternative to electromagnetic actuators in automotive applications, [1]. The existing and potential SMA applications for passenger vehicles are presented in Table 11, which categorizes them according to vehicle functional areas. Most of the selected components are occasionally functioning as linear actuators (e.g. rear-view mirror folding, climate control flaps adjustment and lock/latch controls) and as active thermal actuators (e.g. engine temperature control, carburetion and engine lubrication, and power-train clutches), [2]. However, due to the SMAs attractive morphing capability (active and adaptive structures), the applications are also expanding into other areas, such as aerodynamics and aesthetics applications.

The mechanical simplicity and compactness (miniaturization possibilities) of SMA actuators reduce the scale, weight and cost of automotive components significantly and provide substantial performance benefits in comparison to conventional actuators as demonstrated by the example provided by Neugebauer et al., [3]. The versatility of SMA actuators to adapt with other design mechanisms and techniques such as 'pantograph' for the electrically actuated antiglare rear-view (EAGLE) mirror by Luchetti et al., [4]; make it an excellent actuator for automotive applications.

General Motors (GM) claim that their engineers have been working with SMA applications since the mid-1990s, and it would be likely first implemented on their 2013 model-year cars, [5]. So far GM has earned 247 patents and recently the seventh-generation of the Chevrolet Corvette was to be the first vehicle with a SMA actuator to actuate the hatch vent that releases air from the trunk for easier closing of the trunk lid. Some of their future technologies with SMAs are an electric generator to generate electricity from exhaust heat, a situation-dependent active louver to control the airflow into the engine compartment, on-demand air dam to reduce aerodynamic drag at highway speeds and an adaptive 'grab handle' to ease the opening vehicle doors [6]. Several other SMA applications that have been developed for the automotive industry are the SMA activated automotive tumble flaps to replace conventional electromagnetic and pneumatic effectors, an automatic pedestrian protection system (pop-up bonnet) to minimise pedestrian injuries during impact collisions, a cost effective side mirror actuator, [7], and a micro-scanner system for optical sensing of an objects distance and angle with a FSMA actuator, [8].

Currently, there are many potential applications that have been suggested and these can be found in the patent literature as listed in this work, but only very few of them have actually been implemented or seem technically and economically feasible due to the limited range of SMA transformation temperatures. However, other limitations such as lifetime, hysteresis width, and stability also have to be considered, especially when dealing with extreme conditions and very stringent requirements (e.g. safety). One of the challenges specific to automotive applications is the compatibility of SMA with automotive batteries, this challenge is directly assessed by Leary et al. [9]. The majority of these feasible applications are covered with the commercially available binary NiTi SMA, where its operational temperature range lies approximately within the standard range of environmental temperature extremes to which a passenger vehicle may be exposed during service (i.e. between 40 °C to approx. +125°C, [10]). The standard binary NiTi SMA with transformation temperatures from 50 °C to approximately +110°C [11] performs well for multiple cycles within locations of vehicle within this temperature range, but not in locations with higher temperatures such as under the engine hood. The SMAs should have an Mf temperature well above the maximum operating temperatures in order to work properly.

The idea of this paper is to use specific shape memory alloys to obtain an automotive thermostat to change the water at a certain temperature and to close the evacuation hole of the thermostat when the inside is chilled.

2. EXPERIMENTAL DETAILS

We propose for the metallic active element of the thermostat a Cu-base shape memory alloy. Chemical composition of Cu-Zn-Al shape memory alloys is design taking in account the equilibrium diagram and the variation of M↔A transformation critical points with the chemical elements percentage [12-14]. For the binary alloy Cu-Zn a Ms= 0 °C temperature is obtained at a concentration of 38.5% (at.) Zn and an Ms = -100 °C temperature is obtained for 40% (at.) Zn. For usual brasses with Ms = 0°C β phase isn't stable than in a small domain of high temperature between 850-900°C. In this case is necessary to apply a very fast cooling stage so the β phase to be retain till room temperature and the martensitic transformation, which is the base of shape memory effect, to occur. Aluminum element modifies the equilibrium diagram making the hardening heat treatment less difficult comparing to bi-phase brasses. Among reducing the hardening rate of brasses aluminum increase the corrosion resistance, mechanical resistance and plasticity of the material. A presence of aluminum in 4-8 % at percentages ensures the formation of 9R martensite type fact that gives a good reversibility to M↔A transformation and a small thermal hysteresis. Usual shape memory alloys based on copper has the Ms temperature between -200°C and +100 °C. Chemical composition of a shape memory alloy CuZnAl can be chosen as a function of the Ms value desired between the limits: 62-72% Cu, 14-30% Zn and 4-8% Al [15]. Critical transformation points MS and AS can be calculated with two empirical equations:

$$MS = 2212 - 66.9\,[1.355(\%at.Al) + (\%at.Zn)],{}^{\circ}C \quad (1)$$

$$AS = 2177 - 58.79\,(\%Zn) - 149.64\,(\%Al),{}^{\circ}C \quad (2)$$

The metal load used for alloy elaboration is made of high purity Cu, Zn and Al elements. In order to improve the assimilation yield of Zn and Al pre-alloys with known chemical composition can be used (CuZn and CuAl) and as feeds can be used glass, coke, carbon black, charcoal, borax, SiO_2, CaF_2, Na_3AlF_6, $Na_2\ CO_3$, NaCl, $MgCl_2$, KCl (separately or in combinations). In the melting process we introduce first copper, after the copper melting we introduce aluminum and a part of the solid copper as pre-alloy CuAl in order to decrease the melt overheating based on the aluminum thermal reaction between Al and O and in the end zinc.

The melting temperature is kept below 1200ºC so we reduce the evaporation losses and to favor the gaseous dissolution. To avoid the contamination of the metallic bath the melting occurs with a high rate in high frequency furnaces with graphite crucible and avoiding the formation of aluminum trioxide. For chemical composition correction, fast chemical analyses are made and with dilution or adding elements we manage to obtain the designed chemical composition. The casting temperature is adopted in function of alloy chemical composition using an optimum cooling rate and being without foaming, [16, 17].

The element was analyzed in a laboratory dispositive design as a thermostat element from an actual auto vehicle. On the element was applied to two fasteners so only a part of the shape memory alloy will work under thermal conditions modification.

3. EXPERIMENTAL RESULTS

We realized a thermostat, with a simple design, for automotive industry using a shape memory alloy active element. In figure 1 is present the practical result with the thermostat components. The mechanical part is formed from a brass body provided with a circular section made for water to pass when a certain temperature is reached. After melting the CuZnAl shape memory alloy was homogenized at 800ºC and cold deform by rolling till a plate with 10mm thickness was obtain. The thermo-mechanical training treatment applied to educate the material was previously described, [18].

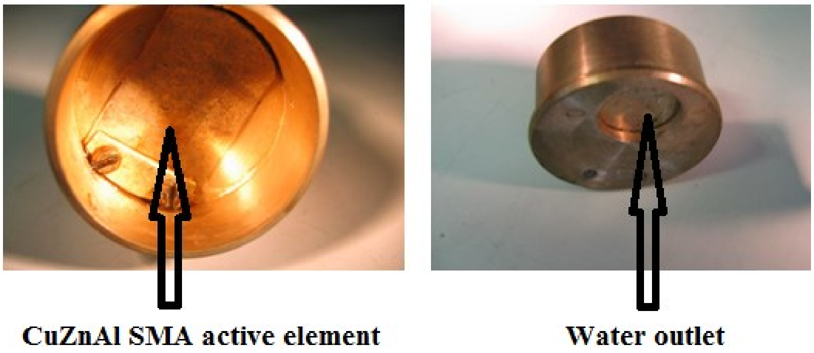


Fig. 1. Experimental new thermostat with shape memory alloy image

As smart element we use a lamella from CuZnAl shape memory alloy, figure 1, that supose to work in 30-100 ºC temperatures range. The thermostat body is dimensioned after an effective thermostat used on the old cars Dacia 1300.

In table 1 are presented the values of critical transformation temperatures As and Af for the experimental alloys. Shape memory elements are lightweight and represent a solid state alternative to usual actuators such as hydraulic, pneumatic and motor-based systems.

In order to establish the usefull domain of functioning domain few standards were used (STAS -8060-83, STAS 8393/18-90; STAS 3160/2-84 or STAS 5055-82). In table 1 are presented the transformation temperatures points As and Af that will start and finish the movement of the active element. The characteristic transformation points presented in table 1 were obtained on differential dilatometer experimental equipment from the dilatation versus temperature curve on heating. Few alloys were design in order to cover the practical necessities from 25 to 99ºC.

The functioning of the thermostat is simple, figure 2, and start with the heating of the water till as temperature moment when the smart active element begin the transformation M→A, figure 2 b), and releases the evacuation hole and finishes when the water temperature reach 70, alloy number 3 from table 1, and the metallic element close the movement.

After the water is chilled under Ms the smart element start to reverse the initial movement and close the evacuation hole, figure 2. The usage of the active element is considered for more than 1 million movements being proper by thermo-mechanical fatigue point of view [19, 20].

Furthermore the element was tested about the heating/cooling time reaction. For heating the element we use the Joule effect applying different currents on the element, even this case is not possible in real application as thermostat, this heating method is similar covering with a thermal flux the entire smart element just like in application the heated water will increase the smart element temperature.

Table 1. Functioning temperatures values of shape memory alloy elements on heating

Alloy nr.	Transformation domain	
	Temperature As	Temperature Af
1	25	37
2	36	48
3	**40**	**70**
4	62	74
5	65	77
6	71	83
7	75	87
8	79	91
9	80	92
10	83	95
11	86	98
12	88	99

Increasing the current applied on the smart element the heating time is decreasing and the opening is faster, table 2. The opening starts around 30˚C and obtains a full aperture till (65-70)˚C based on the heating current used. After the smart element was heated two different cooling conditions were analyzed and registered, table 2.

The difference between the heating and the cooling transition form a hysteresis where a part of the mechanical energy is lost in the process. For one way shape memory effect the movement is realized in its cold state (below As): the metal can be geometrically modified and will hold this shape until a heat is involve till above the transition temperature. Upon heating, in solid state, the lattice modify to its original parameters structure and therefore to its initial form.

Both heating and cooling are dependent of the material thermal properties like thermal conductivity, diffusivity, heat capacity or thermal effusivity. Also the cooling part is dependent of the cooling environment. An important aspect of the shape memory applications is represented by the cooling stage. A nice solution is to diminish the weight of the material and to increase the active area of the element in contact with the environment (in order to improve the heat exchange).

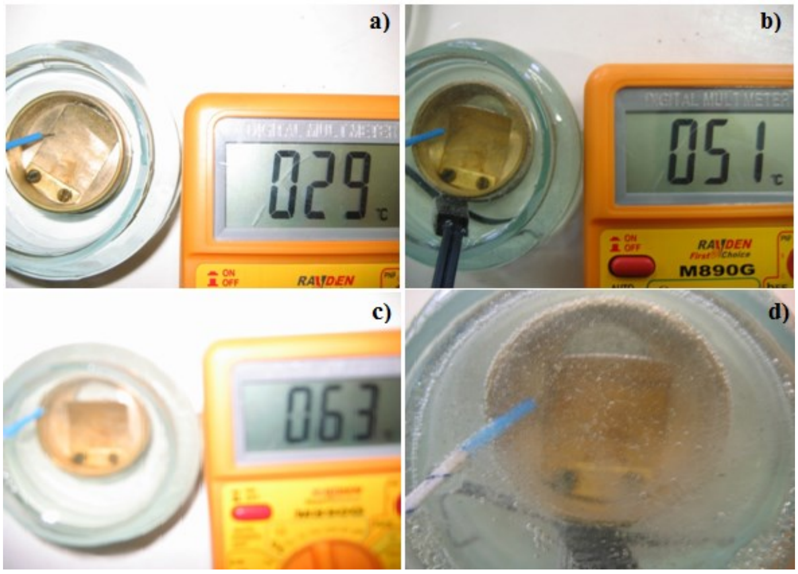
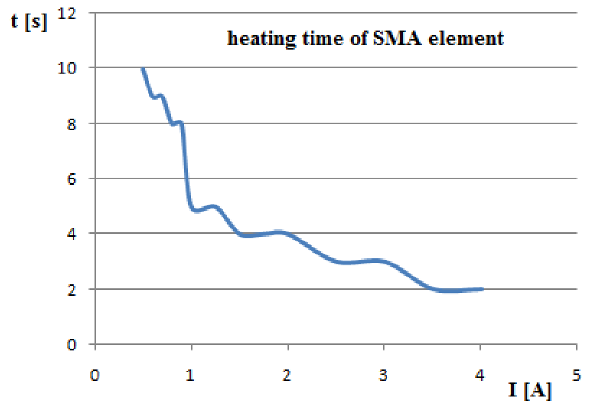
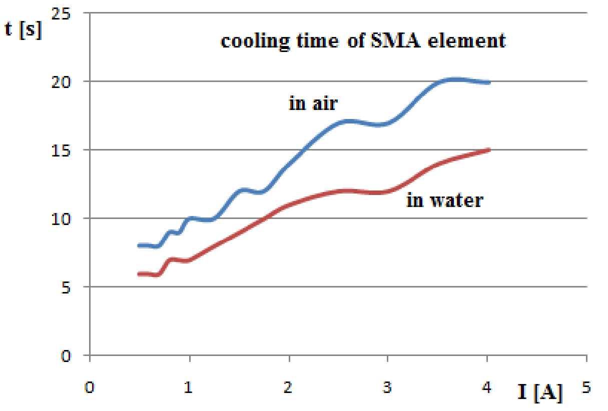


Fig. 2. Images from the thermostat testing a) closed position of the thermostat at 29 ºC b) middle position, c) wide open position at 63 ºC and d) detail of the thermostat in open state

Table 2. Response time of shape memory element at heating, using joule effect and cooling

Current [A]	Heating time [s]	Cooling time [s]	
		in air	in water
0.5	10	8	6
0.6	9	8	6
0.7	9	8	6
0.8	8	9	7
0.9	8	9	7
1.0	5	10	7
1.25	5	10	8
1.5	4	12	9
1.75	4	12	10
2.0	4	14	11
2.5	3	17	12
3.0	3	17	12
3.5	2	20	14
4.0	2	20	15





This can be made by decreasing the element dimensions with the maintaining of the mechanical properties. For this it is necessary a proper design of the element with minimum thicknesses.

Nowadays the need more increased need for speed and power of the automotive equipments suppose to reconsider the design of a thermostat with shape memory alloy active element. New features are established that are based on the properties of the active element most important being connected to the thermal hysteresis dimension (new applications necessity more precise transformation domains), the reaction rate at heating and cooling of the active element, time being a new very valuable variable, and the transformation temperatures domain, an increase need of high temperature shape memory alloys being announced on the industrial market.

4. CONCLUSIONS

Shape memory alloys have many applications in automotive industry and are suitable as classical SMAs and also as HTSMAs. Cu-base shape memory alloy are cheap variant of the shape memory alloys with possible applications in this industry. Based on the vehicle shape memory alloys with different transformation temperatures ranges can be design in order to fulfill the practical requirements. The time response of the shape memory element depend on the re-circulation of water rate and the opening stage is less than 3-5 seconds under the thermal effect. The experimental active element presents a proper behavior for automotive applications. In conclusion the experimental results can be very useful for the actuator industry when SMA activator elements are applied in different domains. More and more opportunities of shape memory elements appear proper to replace the hydraulic, mechanical, electromechanically or pneumatic actuators especially from the automotive industry. For these replacements at industrial scale it is absolutely important to know from the beginning what are the parameters necessary and what the smart materials can offer. This paper present some experimental results CuZnAl shape memory band proposed for automotive industry and also other actuator domain.

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