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On a new electromechanical switch using the reversible wavy elastic response of metallic glass ribbons

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A B S T R A C T

For the first time, practical applications as an alarm device and automatic filling of an aquarium using an electromechanical switch manufactured from metallic glass (MG) ribbon is proposed. The elastic response of an initial arc-shaped MG ribbon-based $Fe_{90.65}B_{3.9}Cr_{2.75}Si_{2.7}$ is studied and exploited. Under the applied load F, the amorphous material exhibits a reversible elastic wavy response. During the elastic deformation and multiplication of harmonic undulations, a perfect linear contact between the waves and support is established. This contact position is the same for the pair waves, and can be employed to ensure the passage of an electric current, since the ribbon is Fe-based. The reversible elastic wavy response of MG ribbon can be used as an electromechanical switch. The lifespan of the ribbon used as a switch is also considered.

1. Introduction

Since the discovery of the amorphous structure in the binary composition $Au_{75}Si_{25}$ in 1960 [1], metallic glasses (MGs) or amorphous alloys have been the main topic of several scientific researches and have been found in many multi-component systems [2]. The specific metallic structure without atomic periodic arrangements of MGs yields to a combination of various mechanical, physical and chemical properties such as superior specific strength, good bending ductility, low friction coefficient, high hardness, high corrosion resistance, and good formability at high temperatures [3–7]. The combination of interesting mechanical and chemical properties makes MGs a valuable option for several applications in different domains, like biomedical fields, surgical devices and instruments [8,9] and sporting items. The super-plastic formability in the super cooled liquid region is useful as well for shape forming and for MEMS and NEMS (Micro and Nano-Electro-Mechanical systems) [10,11].

The main limitation of the use of MGs for structural applications is the catastrophic failure when they deform inhomogeneously at room temperature [12]. Therefore, the use of MGs is frequently related to their super-elasticity (∼2%), and their typical application is in the manufacture of infinite lifetime springs [13]. Recently, Aljerf et al. [14] have shown

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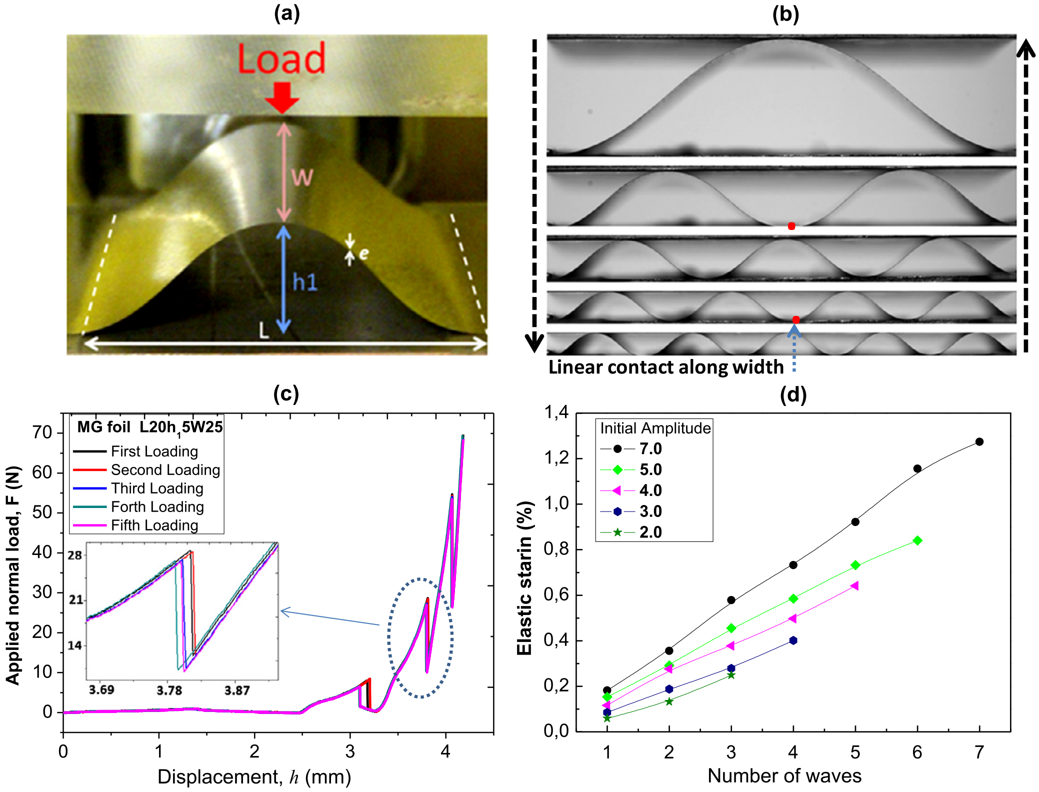

Fig. 1. (a) Initial arc-shaped metallic glass (MG) ribbon with $L = 20$ mm, $h_1 = 5$ mm, $W = 25$ mm, and $e = 0.019$ mm. (b) Experimental wavy elastic response of an arc-shaped MG ribbon with five formed waves. (The black pointed arrows show the direction of loading and unloading.) (c) Evolution of the normal applied load F versus the displacement, h, during several loadings. (d) Elastic deformation versus number of formed waves for various initial amplitudes.

the thermomechanical wavy shaping of vitrified ribbon without thermal embrittlement. In our recent work [15], we have experimentally showed the possible use of the reversible wavy elastic response as a novel micro-flat-spring.

In the current work, we focused on the exploitation of the wavy elastic response of MG ribbon as an electromechanical switch. We suggest a practical application of an alarm device and an automatic filling of an aquarium using MG ribbons.

2. Experimental procedure and results

When the initial arc-shaped metallic glass ribbon-based $Fe_{90.65}B_{3.9}Cr_{2.75}Si_{2.7}$ is subjected to a normal load F, it exhibits a specific reversible wavy elastic response. The initial arc presents the dimensions shown in Fig. 1(a), where L represents the boundary distance for the lateral fixation, h_1 the initial amplitude, W the width of the ribbon (25 mm), and e the nominal thickness of 19 µm. L and h_1 have been chosen experimentally to satisfy the experimental relationship $h_1/L \leq 1/2$.

As shown in Fig. 1(b), under a progressive normal loading F, MG ribbon exhibits a reversible wavy elastic response. This behavior involves linear contact positions along the width when the undulations appear. Furthermore, the response is symmetric at $L/2 = 10$ mm. Fig. 1(c) shows the evolution of the applied load F versus the displacement, h ($h = h_1 – h_i$, $1 \leq i \leq n$, n: number of waves). It presents the same reversible wavy response for several loadings. If we consider R as the radius of curvature of the wave, the elastic strain ε_{elas} could be estimated according to [14]:

$$R = \frac{e}{2 \cdot \varepsilon_{elas}} \quad (1)$$

Fig. 1(d) shows the elastic strain versus the number of formed waves. Using the ribbon with $L = 20$ mm, $h_1 = 5$ mm, we can reach six waves equivalent to 0.83% of the elastic strain ($\ll$2%, the material is always in the elastic field). From Fig. 1(d), and because of the experimental conditions ($h_1/L \leq 1/2$), the number of formed waves increases with the initial amplitude h_1, and consequently the boundary distance L.

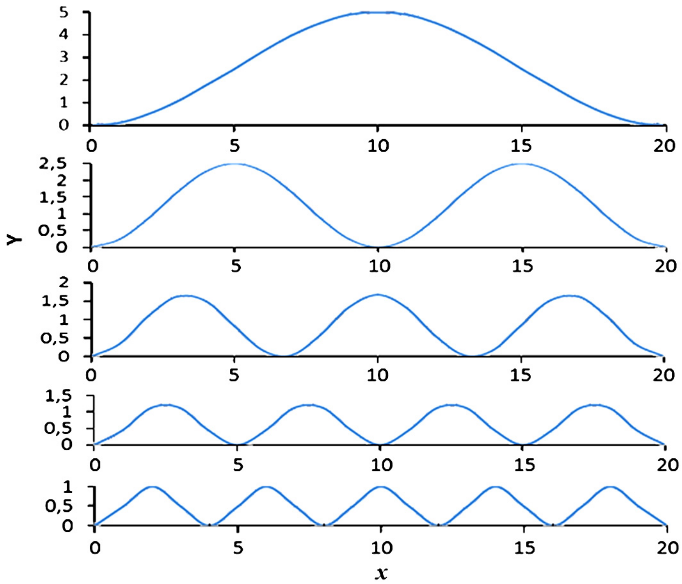

Fig. 2. Numerical resolution of Eq. (2) for $n = 5$, which describes the wavy response of MG ribbon subjected to a normal load F. The same linear contact position for pair waves at $x = 10$ mm.

Based on Fig. 1(b), a multiplication of waves is created during loading. The initial amplitude h_1 decreases versus the number of created waves and the metallic glass ribbon presents a sinusoidal response that could be described by the equation:

$$Y(x) = h_1 \sin^2\left(n \cdot \frac{2\pi}{\lambda} \cdot x\right) \tag{2}$$

where n is the number of waves and λ the wavelength ($\lambda = 2L/n$). The numerical resolution of Eq. (2) is shown in Fig. 1(d), and describes perfectly the wavy response of the MG ribbon subjected to the normal load F. One notes symmetric curves at $L/2$. Based on this equation, the linear contact positions could be precisely localized for each number of formed waves. Furthermore, for the ribbon with $L = 20$ mm, $h_1 = 5$ mm, and according to Fig. 2, the same linear contact is established for the pair waves (2, 4, 6, etc.) at $x = 10$ mm. The same specific elastic response is experimentally well shown in Fig. 1(b).

The aim of this work is to exploit the linear contact positions established by the formed waves during the elastic deformation (loading), to ensure and control the passage of an electric current.

3. Novel electromechanical switch from metallic glass ribbon

Electromechanical switches are widely used in electrical and mechanical systems such as motors, buildings, medicine, aviation, sports, automotive fields [16,17]. They are found in several types: electrical, safety and position switches, pressure or force sensors, etc. The setting of these switches is based on the passage and electrical power control in order to effectively monitor or stop a system. In the present section, we propose a new switch made from a metallic glass ribbon to control an alarm device and to fill automatically an aquarium.

As they are mainly $Fe_{90.65}B_{3.9}Cr_{2.75}Si_{2.7}$ iron based, metallic glass ribbons conduct perfectly the current. Furthermore, using the observed wavy response in Fig. 1(b), these ribbons can be adjusted to the realization of switches for industrial applications. Fig. 3 shows a schematic device of an electrical circuit involving a metallic glass ribbon. According to Fig. 3, when the load increases, a new contact occurs and the LED lights up. This indicates the presence of an electrical voltage in the circuit and the current flows through the ribbon. The positions of the extrema (minimum and maximum) of the formed waves could be operated as a linear contact position, as indicated in Fig. 1(b). Another property of a metallic glass ribbon is that it has the same contact in each pair number of waves (see red contact points in Fig. 1(b)). It could also be used to simultaneously control the passage of many signals. Fig. 3(b) and (d) show that the green LED lights for two and four waves simultaneously. Thus, many systems could be commanded at the same time or alternatively when linear contacts with pair waves are used.

In order to further explain the activation of the LED versus time, Fig. 4 presents the chronogram displaying the state of each LED during loading on the arc-shaped MG ribbon according to the number of formed waves. The green LED operates simultaneously four two and four waves.

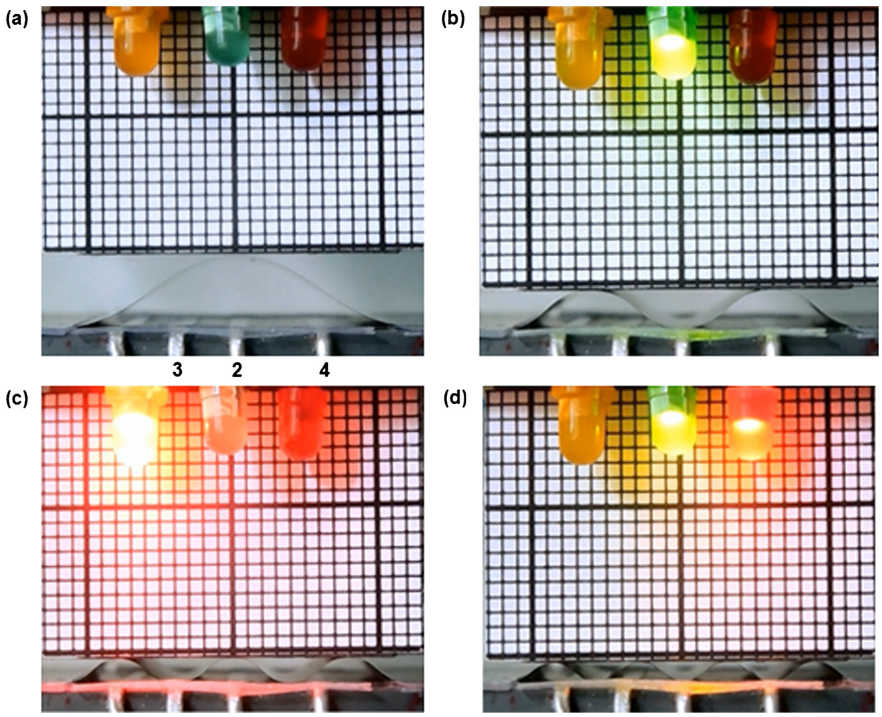

Fig. 3. Photos showing the wavy elastic response of MG ribbon used as an electromechanical switch. (a) First arc-shaped: no LED lights, (b) two created waves: green LED lights, (c) three created waves: orange LED lights, and (d) four created waves: both green and red LED light. In figure (a): 2, 3, and 4 indicate the linear contact along width when two, three, and four waves appear respectively.

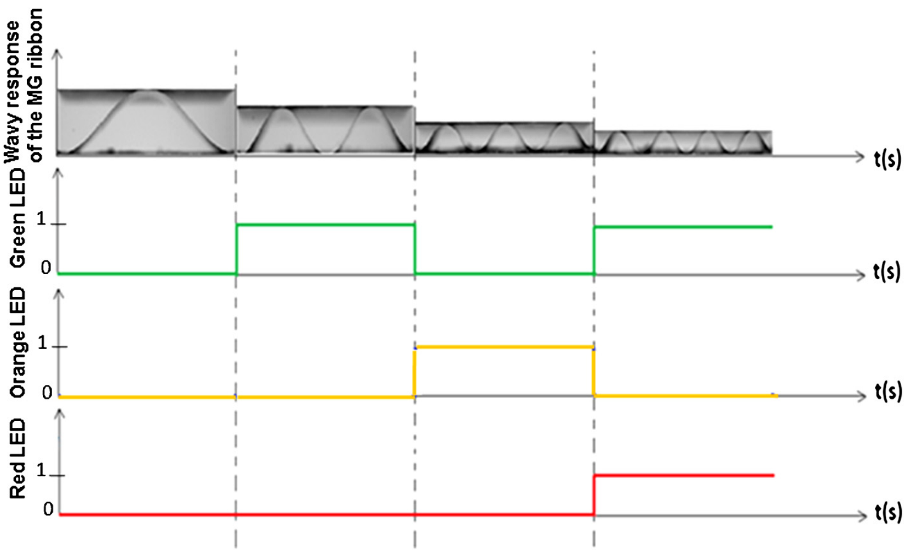

Fig. 4. Chronogram of activation LED for each linear contact position. Alternating operation for pair waves (2, 4, 6, etc.).

4. Application of MG ribbon used as an electromechanical switch

4.1. Application for alarm devices

Based on Fig. 3, the wavy elastic response of MG ribbon could be used as a switch in many applications such as alarm systems. For example, a device could be protected against overweight, by controlling the loading limit using MG ribbon as shown in Fig. 5.

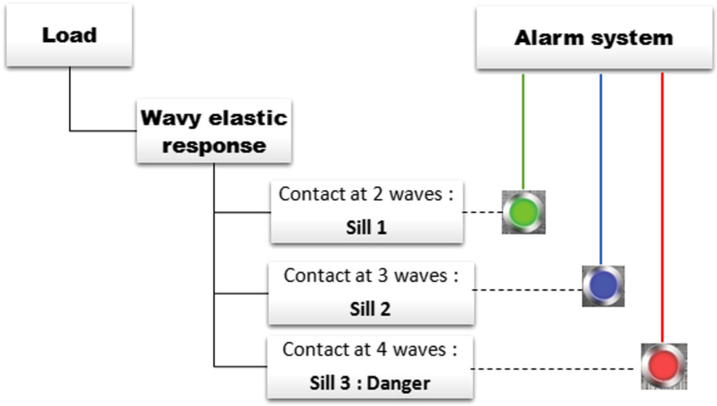

Fig. 5. Usage of MG ribbon as a switch to control the alarm device. Sill 1: two waves reached, sill 2: three waves reached, and sill 3: four waves reached: Danger or risk (red alarm).

4.2. Application for the automatic filling of an aquarium

4.2.1. Design

The purpose is to use a wavy elastic response of MG ribbon as a switch to ensure and control the filling of an aquarium without human intervention. This application is useful for people traveling for a long period or having a long stay away from their households. The aquarium is an ecological enclosure used to ensure an optimum environment for fish life. It is composed of two compartments: the first one covers the tank, the pump and the sensors. The second contains the motor and the rack-pinion system that induces a normal applied force on the arc-shaped MG ribbon. The ribbon, which is integrated to control the system, allows a great stability for an optimum safety operating. In case of prolonged absence, the present designed system allows automatic tank filling.

4.2.2. Electrical wiring and implementation

Fig. 6 shows a schema for the electric aquarium's wiring, with the automatic device ensuring tank filling when necessary.

The tank of the aquarium is initially filled and lighted for the ecological cycle of fishes. This induces water evaporation, which progressively reduces the total volume by 5% per day at most, depending on the climatic conditions.

The designed idea is to set a sensor on the wall of the glass with well-defined high and low levels. The sensor behaves like a switch to turn "on" and "off" the motor-pump "M–P" (see Fig. 6). The control and command of the system are accomplished by using an electronic card.

If the water level is above the normal value (aquarium filled), the float is in the up position "off", and the pump does not work. If the water level becomes below the normal value, that means the water has reached level 1, a signal from sensor S_1 is sent to the electronic card, then the motor starts rotating in the first sense to ensure a displacement as a course $C_1 = 3.8$ mm (C_1 is the total displacement from the first arc-shaped to three formed waves for the ribbon with dimensions $L = 20$ mm, $h_1 = 5$ mm calculated from Fig. 1(c)). The MG ribbon is elastically deformed and 2 waves are reached. Thus, the first linear contact position is made (blue point in Fig. 6), then a signal is sent to the electronic card to make the pump "on" and filling starts. The filling operation continues until the development of three waves (end of C_1: red point in Fig. 6); another signal will be sent to the electronic card to make motor "**M**" in the second rotation sense. Finally, motor "**M**" returns to the first position and filling stops. What is interesting in this work is that it is the first time that a metallic glass ribbon is used in a practical application as an electromechanical switch exploiting its specific elastic wavy response.

4.3. Lifespan of the MG ribbon subjected to cyclic loading

The number of cycles to failure of a metallic glass ribbon used as an electromechanical switch for the automatic filling of an aquarium is measured based on the activation of three undulations. Thus, a cyclic loading with a frequency of 0.27 Hz corresponds to the displacement range between the initial arc-shaped and 3, 4, and 5 undulations. The designed set-up to measure the number of cycles to failure is showed in Fig. 7. This device is realized at the SIMaP laboratory, INP Grenoble, France, and is mainly composed of a support to fix the arc-shaped ribbon and of a motor to ensure the cyclic translational movement (normal loading step).

Fig. 8 shows the number of cycles to failure for various formed waves (3, 4, and 5) for the same MG ribbon dimensions ($L = 20$ mm, $h_1 = 5$ mm, $W = 25$ mm, and $e = 0.019$ mm) with their corresponding load and the elastic deformation, which remains well below the elastic limit of 2%. The failure presents the formation and propagation of fatigue crack that distorts the reversibility of the elastic deformation of the pre-deformed MG ribbon. For three formed waves, the load and elastic strain are lower, but the lifespan is higher (around 7100 cycles for 30 N as the load and 0.46% as the elastic strain). For the higher applied load and consequently the higher elastic strain, the lifespan decreases (around 1300 cycles for 80 N as

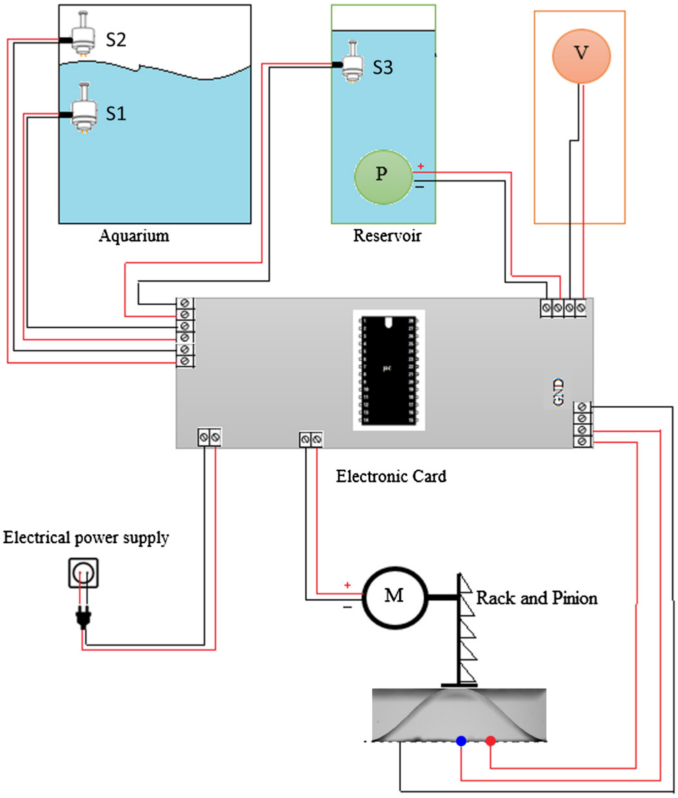

Fig. 6. Schema of the electrical wiring for the automatic filling of an aquarium using a reversible elastic wavy response of an MG ribbon as an electromechanical switch.

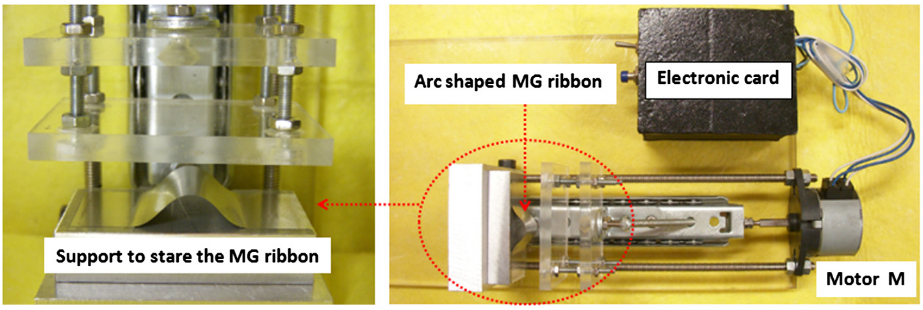

Fig. 7. Set-up used to estimate the number of cycles to failure of an MG ribbon when the wavy response is used as an electromechanical switch.

the load and 0.74% as the elastic strain). This experimental result is common because, when the material is more elastically stressed (or loaded), its lifespan decreases. This result was confirmed by Zhen et al. [18].

When three waves are exploited for the automatic filling of an aquarium system, the lifespan is 7100 cycles, corresponding to an elastic deformation of 0.46%. The lifespan of the electromechanical switch decreases with the increase of the formed waves and, consequently, with elastic deformation, as shown in Fig. 8(a) and (b). The lifespan of MG ribbon that exceeds 7000 cycles used as an electromechanical switch is better than the lifespan of a conventional steel material using elastic deformation [17].

In order to explain the potential causes of the failure of MG ribbon when it is used as an electromechanical switch, high-resolution scanning electronic microscope examinations were conducted in the CMTC (INP Grenoble). Fig. 9 shows SEM images of the ribbon immediately after failure when the cyclic loading is conducted from the initial arc-shaped to the four formed waves.

Fig. 9(a) shows that the first crack tips are due to the surface defects created during the elaboration process of the ribbon (see red arrows). These defects could be a preferential site for crack initiation. Wang et al. [19] have considered that the casting defects are one of the important features for the initial step of the fatigue cracks. Fig. 9(b) and (c) show the creation and propagation of shear bands around the crack. Thus, the main cause of crack initiation lies in the casting defects

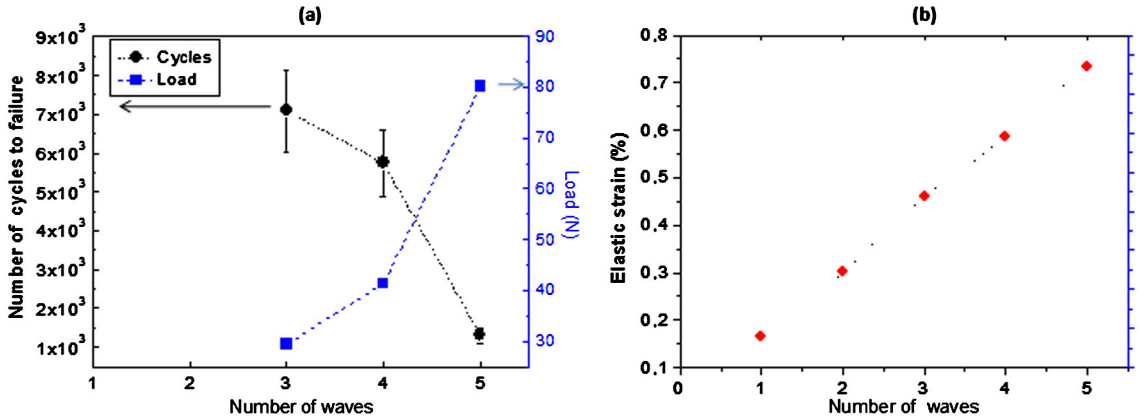

Fig. 8. (a) Number of cycles to failure (lifespan) versus the waves used as an electromechanical switch and their corresponding load F. (b) Maximum level of elastic deformation for each wave.

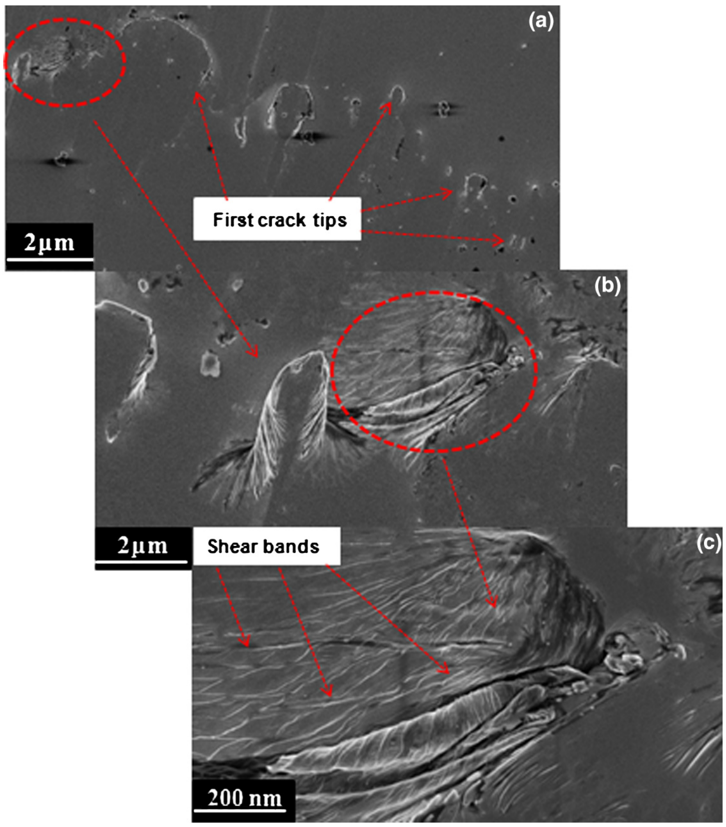

Fig. 9. SEM images of the surface of the ribbon after failure. (a) The red arrows show the first crack tips due to surface defects; (b) and (c), creation and propagation of many shear bands during crack propagation.

during the preparation of the ribbon. Furthermore, no plastic deformation was observed away from defects and Fig. 8(b) confirms that the ribbon remains in elastic deformation even for five waves. The fatigue endurance of MG ribbon depends on the surface defects, and the cycling lifespan could be increased if these defects were reduced through surface treatment techniques.

5. Concluding remarks

Under a normal load applied on initial arc-shaped metallic glass ribbons, the material exhibits a reversible wavy elastic response. This response, composed of sinusoidal undulations, is characterized by the linear contact along the width of the ribbon (contact between waves and support), which can be used to ensure and control the electrical circuit. Thus, the reversible wavy elastic response can be exploited as an electromechanical switch. The pair waves present the same linear contact position that can be used when there is an alternating function in the system. For the first time, we propose practical applications as an “alarm device” and for the “automatic filling of an aquarium”, using an electromechanical switch manufactured from the wavy elastic response of MG ribbon. The lifespan of MG ribbon used as an electromechanical switch using three waves exceed 7000 cycles and could be increased more through surface treatment techniques to reduce the casting defects.

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References

[1] W. Klement, R. Willens, P. Duwez, Non-crystalline structure in solidified gold–silicon alloys, Nature 187 (1960) 869–870.
[2] A. Inoue, Stabilization of metallic supercooled liquid and bulk amorphous alloy, Acta Mater. 48 (2000) 279–306.
[3] C. Suryanarayana, A. Inoue, Bulk Metallic Glasses, CRC Press, Boca Raton, FL, USA, 2011.
[4] M.D. Demetriou, A. Wiest, D.C. Hofmann, W.L. Johnson, B. Han, N. Wolfson, G.Y. Wang, P.K. Liaw, Amorphous metals for hard-tissue prosthesis, JOM 62 (2010) 83–91.
[5] J. Schroers, G. Kumar, T.M. Hodges, S. Chan, T.R. Kyriakides, Bulk metallic glasses for medical applications, JOM 61 (2009) 21–29.
[6] D. Zander, B. Heisterkamp, I. Gallino, Corrosion resistance of Cu–Zr–Al–Y and Zr–Cu–Ni–Al–Nb bulk metallic glasses, J. Alloys Compd. 434–435 (2007) 234–236.
[7] D.M. Herlach, R.F. Cochrane, I. Egry, H.J. Fecht, A.L. Greer, Containerless processing in the study of metallic melts and their solidification, Int. Mater. Rev. 38 (1993) 273–347.
[8] H.F. Li, Y.F. Zheng, Recent advances in bulk metallic glasses for biomedical applications, Acta Biomater. 36 (2016) 1–20.
[9] Y. Liu, G. Wang, H. Li, S. Pang, K. Chen, T. Zhang, Ti–Cu–Zr–Fe–Sn–Si–Sc bulk metallic glasses with good mechanical properties for biomedical applications, J. Alloys Compd. 679 (2016) 341–349.
[10] A. Lindsay Greer, Metallic glasses… on the threshold, Mater. Today 12 (2009) 14–22.
[11] D.S. Nguyen, E. Halvorsen, G.U. Jensen, A. Vogl, Fabrication and characterization of a wideband MEMS energy harvester utilizing nonlinear springs, J. Micromech. Microeng. 20 (2010) 125009.
[12] C.A. Schuh, T.C. Hufnagel, U. Ramamurty, Mechanical behavior of amorphous alloys, Acta Mater. 55 (2007) 4067–4109.
[13] K. Sona, H. Soejima, N. Nishiyama, X.-M. Wang, A. Inoue, Process development of metallic glass wires by a groove quenching technique for production of coil springs, Mater. Sci. Eng. A 449–451 (2007) 248–252.
[14] M. Aljerf, K. Georgarakis, A.R. Yavari, Shaping of metallic glasses by stress-annealing without thermal embrittlement, Acta Mater. 59 (2011) 3817–3824.
[15] M.A. Yousfi, N.T. Panagiotopoulos, A.M. Jorge Junior, K. Georgarakis, A.R. Yavari, Novel micro-flat springs using the superior elastic properties of metallic glass foils, Scr. Mater. 131 (2017) 84–88.
[16] A.H. El-Sinawi, M. Bakri-Kassem, T. Landolsi, O. Awad, A novel comprehensive approach to feedback control of membrane displacement in radio frequency micro-electromechanical switches, Sens. Actuators A, Phys. 221 (2015) 123–130.
[17] D.G. Khushalani, R.S. Pande, R.M. Patrikar, Fabrication and characterization of MEMS cantilever array for switching applications, Microelectron. Eng. 157 (2016) 78–82.
[18] Z.-Q. Song, Q. He, E. Ma, J. Xu, Fatigue endurance limit and crack growth behavior of a high-toughness $Zr_{61}Ti_2Cu_{25}Al_{12}$ bulk metallic glass, Acta Mater. 99 (2015) 165–175.
[19] G.Y. Wang, P.K. Liaw, A. Peker, B. Yang, M.L. Berson, W. Yuan, W.H. Peter, L. Huang, M. Freels, R.A. Buchanan, C.T. Liu, C.R. Brooks, Fatigue behavior of Zr–Ti–Ni–Cu–Be bulk-metallic glasses, Intermetallics 13 (2005) 429–435.