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

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Abstract

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. Elastic response of an initial arch shaped MG ribbon based- $\text{Fe}_{90.65}\text{B}_{3.9}\text{Cr}_{2.75}\text{Si}_{2.7}$ 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 based-Fe. 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.

Keywords

Metallic glass ribbon, reversible elastic wavy response, practical electromechanical switch applications, lifespan.

1. Introduction

Since the discovery of the amorphous structure in the binary composition $\text{Au}_{75}\text{Si}_{25}$ 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 ductility in bending, low coefficient of friction, high hardness, high resistance and corrosion 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 the 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 its super-elasticity ($\sim 2\%$) and the typical application is the usefulness for the manufacture of infinite lifetime springs [13]. Recently, Aljerf et al [14] have shown the thermomechanical wavy shaping of vitrified ribbon without thermal embrittlement. In our recent work [15], we experimentally showed the possible use of the reversible wavy elastic response as a novel micro-flat-spring.

In the current work, we focus on the exploitation of the wavy elastic response of MGs 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 $\text{Fe}_{90.65}\text{B}_{3.9}\text{Cr}_{2.75}\text{Si}_{2.7}$ is subjected to a normal load F , it exhibits a specific reversible wavy elastic response. The initial arc presents the dimensions shown in figure 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 . h_1 and L have been experimentally chosen to satisfy the experimental relationship $h_1/L \leq 1/2$.

As shown in figure 1(b), under a progressive normal loading F , MGs ribbon exhibits a reversible wavy elastic response. This behavior shows a linear contact positions along the width when the undulations appear. Furthermore, the response is symmetric at $L/2=10\text{mm}$. Figure 1(c) shows the evolution of the applied load F versus 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]:

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

Fig.1(d) shows the elastic strain versus the number of formed waves. Using the ribbon with $L=20\text{mm}$, $h_1=5\text{mm}$, we can reach 6 waves equivalent to 0.83% of elastic strain ($\ll 2\%$, the material is always in elastic field). According to fig.1(d) and experimental condition ($h_1/L \leq 1/2$), the number of formed waves increases versus the initial amplitude h_1 and consequently the boundary distance L .

Based on the 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:

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

Where n is the number of waves and λ the wavelength ($\lambda=2L/n$). The numerical resolution of the equation (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 localized precisely for each number of formed waves. Furthermore, for the ribbon with $L=20\text{mm}$, $h_1=5\text{mm}$ and according to fig.2, the same linear contact is established for the pair waves (2, 4, 6, etc..) at $x=10\text{ mm}$. The same specific elastic response is well shown experimentally 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 switches, safety switches, position switches, pressure or force sensors... etc. The setting of these switches is based on the passage and control of electrical power 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 automatic filling of an aquarium.

As they are mainly based on iron $\text{Fe}_{90.65} \text{B}_{3.9} \text{Cr}_{2.75} \text{Si}_{2.7}$, metallic glass ribbons conduct perfectly the current. Furthermore, using the observed wavy response of fig.1(b), these ribbons can be adjusted to the realization of switches for industrial applications. Figure.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. This indicates the presence of an electrical voltage in the circuit and the current flows through the ribbon. The positions of extrema (minimum and maximum) of formed waves could be operated as a linear contact positions 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 be also used to control simultaneously the passage of many signals. Fig.3 (b) and (d) show that green LED lights for 2 and 4 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 the time, figure.4 presents the chronogram displaying the state of each LED during the loading on the arc shaped MG ribbon according to the number of formed waves. The green LED operates simultaneously at 2 and 4 waves.

4. Application of MGs ribbon used as an electromechanical switch

4.1. Application for Alarm device

Based on figure 3, the wavy elastic response of MGs 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 MGs ribbon as shown in figure.5.

4.2. Application for Automatic filling of an aquarium

4.2.1. Design

The purpose is to use a wavy elastic response of MGs ribbon as a switch to ensure and control the filling of an aquarium without human intervention. This application is useful for people travelling 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 MGs ribbon. The ribbon, which is integrated to control the system, allows a great stability for an optimum operating safety. In case of prolonged absence, the present designed system allows an automatic filling of the tank.

4.2.2. Electrical wiring and implementation

Figure.6 shows a schema for the electric wiring of the aquarium with the automatic device ensuring the filling of the tank when it is necessary.

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

The design 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 figure.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”, the pump does not work. If the water level becomes below the normal value, that means the water has reaches level 1, a signal from sensor S_1 is sent to the electronic card, then the motor starts rotating in the 1st sense to ensure a displacement as a course $C_1 = 3.8 \text{ mm}$ (C_1 is the total displacement from the first arc shaped to 3 formed waves for the ribbon with dimensions $L=20\text{mm}$, $h_1=5\text{mm}$ calculated from fig.1(c)). 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 3 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, the motor “M” returns to the first position and the filling stops. The interesting thing 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 an automatic filling of an aquarium is measured based on the activation of 3 undulations. Thus, the 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 figure 7. This device is realized at SIMaP laboratory-Grenoble INP-France and composed mainly of a support to fix the arc shaped ribbon and a motor to ensure the cyclic translational movement (normal loading step).

Figure.8 shows the number of cycles to failure for various formed waves (3, 4 and 5) for the same MG ribbon dimensions ($L=20\text{mm}$, $h_1=5\text{mm}$, $W=25\text{mm}$ and $e=0.019\text{mm}$) with their corresponding load and the elastic deformation that 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 3 formed waves, the load and elastic strain are lower but the lifespan is higher (around 7100 cycles for 30N as load and 0,46% as elastic strain). For the higher applied load and consequently the higher elastic strain, the lifespan decreases (around 1300 cycles for 80N as load and 0,74% as 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 3 waves are used for the automatic filling of an aquarium system, the lifespan is 7100 cycles corresponding to the elastic deformation of 0.46%. The lifespan of the electromechanical switch decreases with the increase of formed waves and consequentially 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 CMTC-Grenoble-INP. Fig.9 shows SEM images of the ribbon immediately after failure when the cyclic loading is conducted from the initial arc shaped to the 4 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 a creation and propagation of shear bands around the crack. Thus, the main cause of the crack initiation is due to the casting defects 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 5 waves. The fatigue endurance of MG ribbon depends on the surface defects and the cycling lifespan could be increased if these defects are 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 passage circuit of an electric current. 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 “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 3 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, 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, and I. Gallino, Corrosion resistance of Cu–Zr–Al–Y and Zr–Cu–Ni–Al–Nb bulk metallic glasses, *Journal of Alloys and Compounds*. 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, *Inter Mater Reviews*. 38 (1993) 273-347.
- [8] H.F. Li, Y.F. Zheng, Recent advances in bulk metallic glasses for biomedical applications, *Acta Biomaterialia*. 36 (2016) 1-20.
- [9] Ying Liu, Guan Wang, Haifei Li, Shujie Pang, Kewei Chen, Tao Zhang, Ti-Cu-Zr-Fe-Sn-Si-Sc bulk metallic glasses with good mechanical properties for biomedical applications, *J of Alloys and Compounds*. 679 (2016) 341-349.
- [10] A. Lindsay Greer, Metallic glasses... on the threshold, *Materials 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 and U. Ramamurty, Mechanical behavior of amorphous alloys, *Acta Mater.* 55 (2007) 4067-4109.
- [13] Kunsu Sona, Hideki Soejima, Nobuyuki Nishiyama, Xin-Min Wang, Akihisa Inoue, Process development of metallic glass wires by a groove quenching technique for production of coil springs, *Mater Sci and 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, *Scripta Mater.* 131 (2017) 84–88.
- [16] Ameen H. El-Sinawi, Maher Bakri-Kassem, Taha Landolsi, Omar Awad. A novel comprehensive approach to feedback control of membrane displacement in radio frequency micro-electromechanical switches, *Sensors and Actuators A: Physical.* 221(2015) 123-130
- [17] Deepak G. Khushalani, Rajesh S. Pande, Rajendra M. Patrikar, Fabrication and characterization of MEMS cantilever array for switching applications, *Microelectronic Engineering.* 157 (2016) 78-82.
- [18] Zhen-Qiang Song, Qiang He, Evan Ma, Jian Xu, Fatigue endurance limit and crack growth behavior of a high-toughness, $\text{Zr}_{61}\text{Ti}_2\text{Cu}_{25}\text{Al}_{12}$ 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 and C. R. Brooks, Fatigue behavior of Zr-Ti-Ni-Cu-Be bulk-metallic glasses, *Intermetallics.* 13 (2005) 429-435.

Figure Captions

Figure.1. Figure.1.(a) Initial arc shaped metallic glass (MG) ribbon with $L=20\text{mm}$, $h_1=5\text{mm}$, $W=25\text{mm}$ and $e=0.019\text{mm}$, (b) Experimental wavy elastic response of arc shaped MG ribbon with 5 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 and (d) Elastic deformation versus the number of formed waves for various initial amplitudes.

Figure.2. Numerical resolution of Eq(2) for $n=5$ that describes the wavy response of MG ribbon subjected to normal load F . The same linear contact position for pair waves at $x=10\text{ mm}$.

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

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

Figure.5. Usage of MG ribbon as a switch to control alarm device. Sill 1: 2 waves reached, Sill 2: 3 waves reached and Sill3 when 4 waves reached: Danger or risk (Red alarm).

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

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

Figure.8. (a) Number of Cycles to failure (Lifespan) versus used waves as an electromechanical switch and their corresponding load F , (b) Maximum level of Elastic deformation for each wave.

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

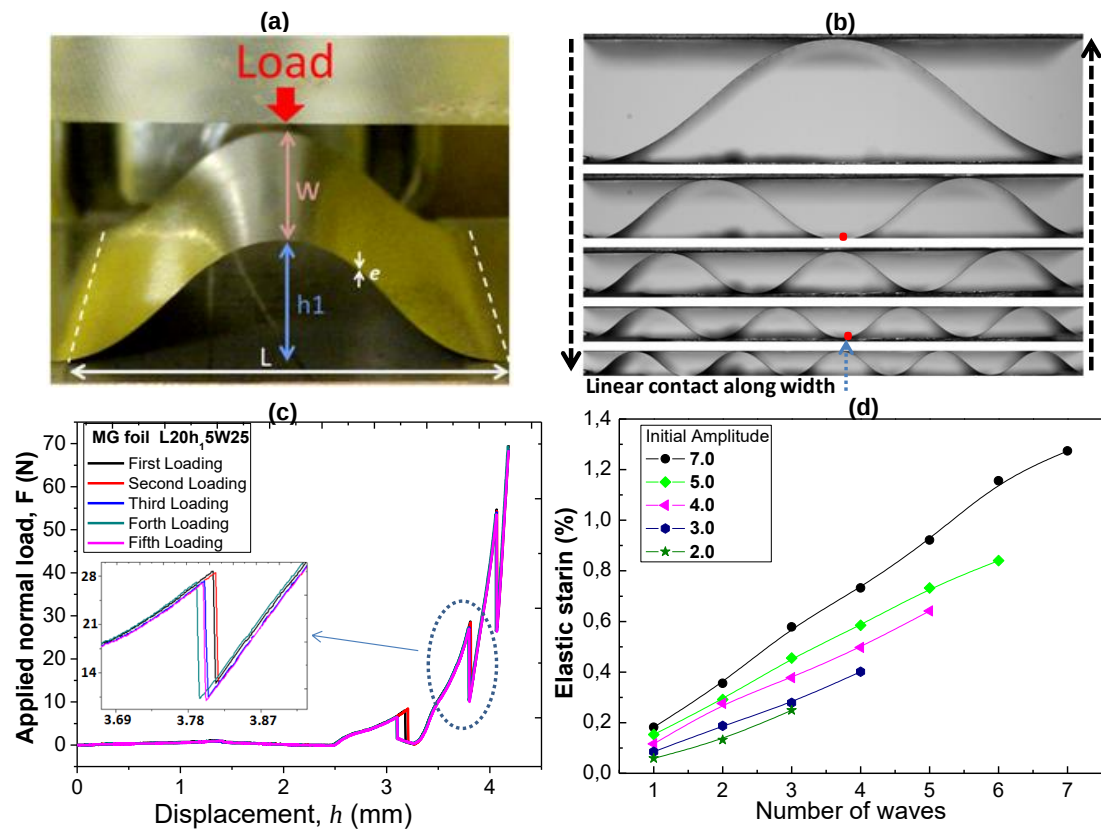


Figure.1

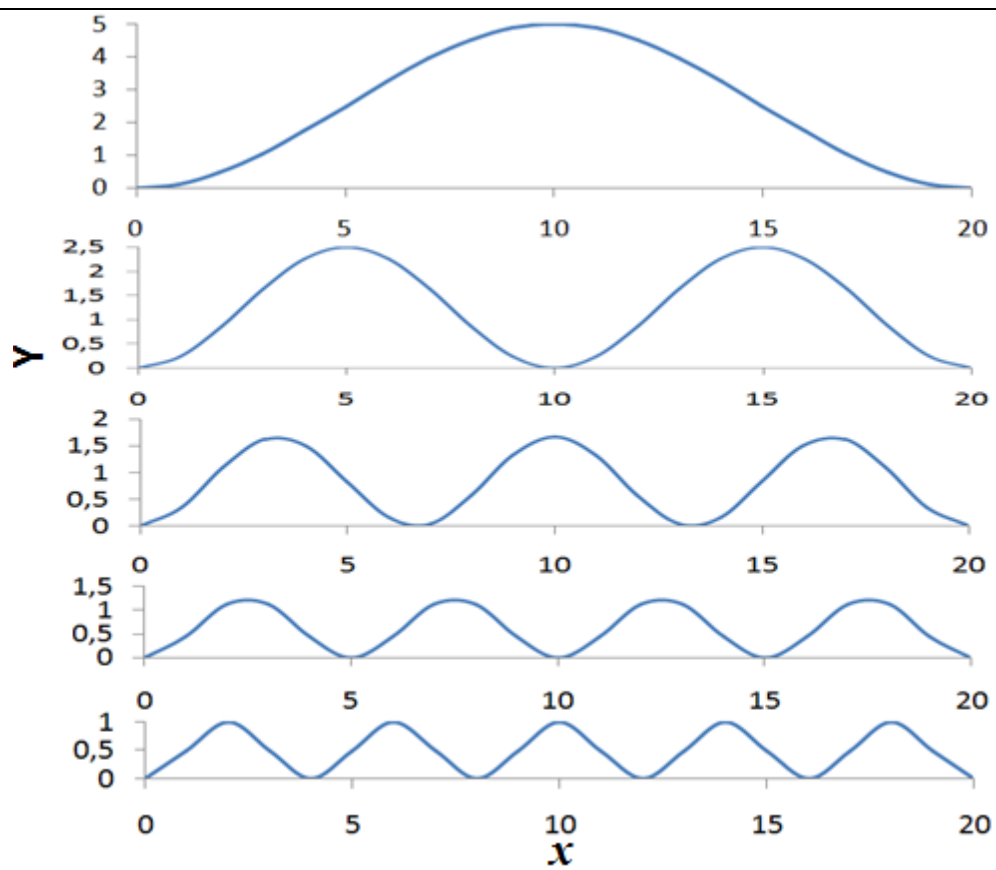


Figure.2

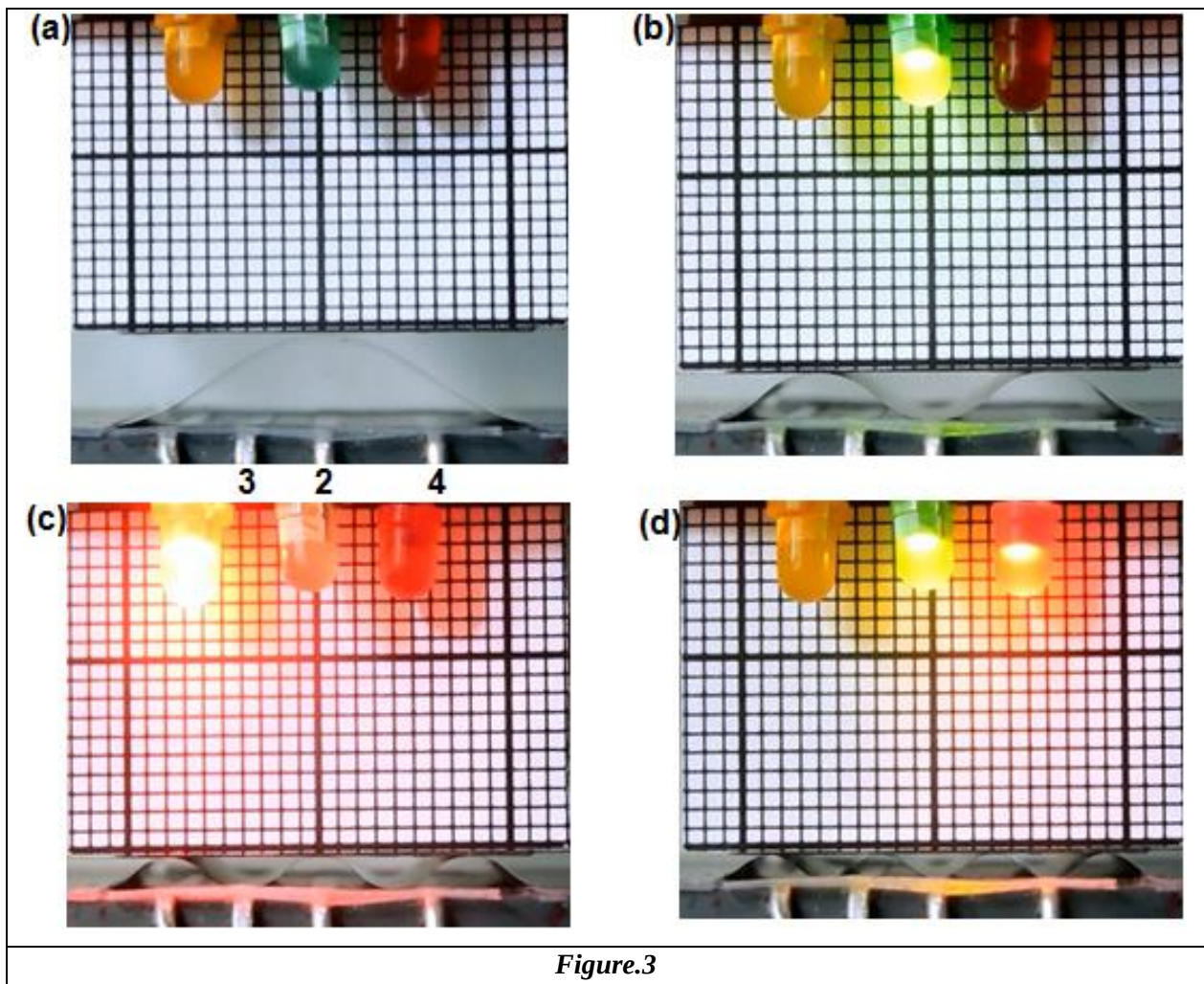


Figure.3

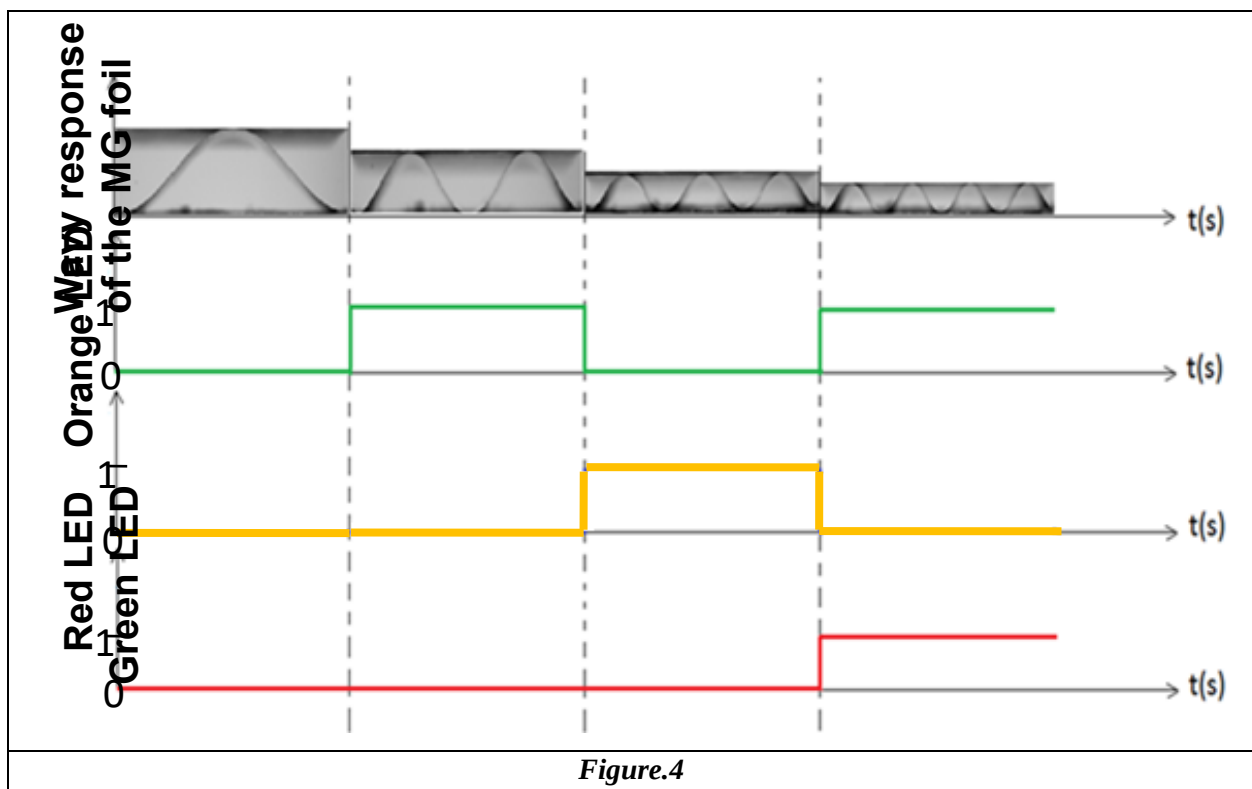


Figure.4

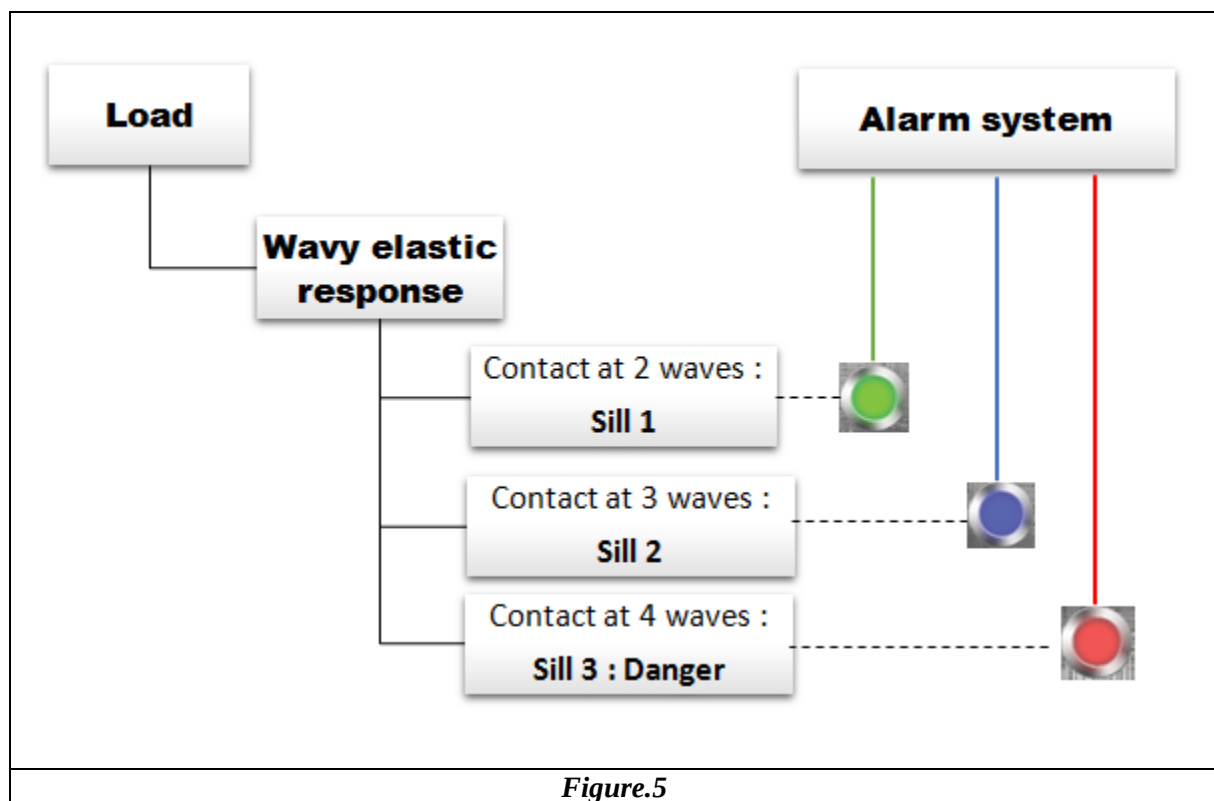
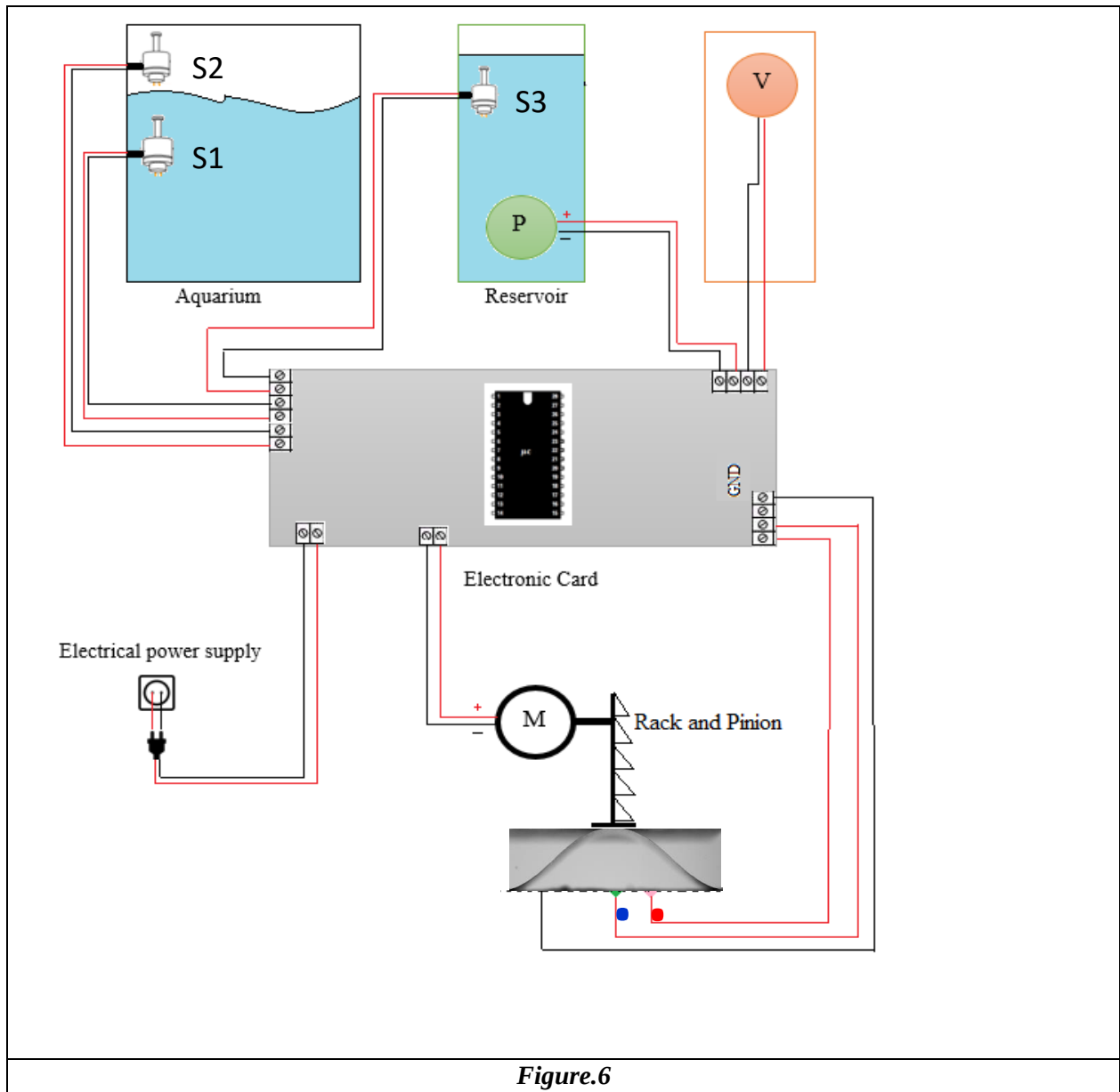
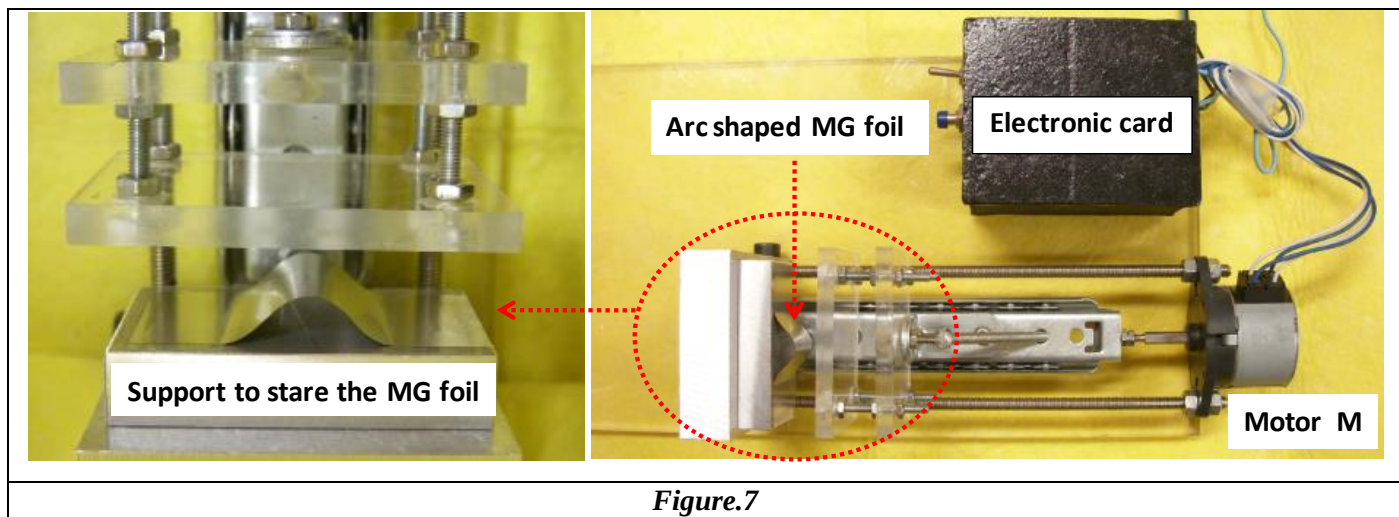


Figure.5





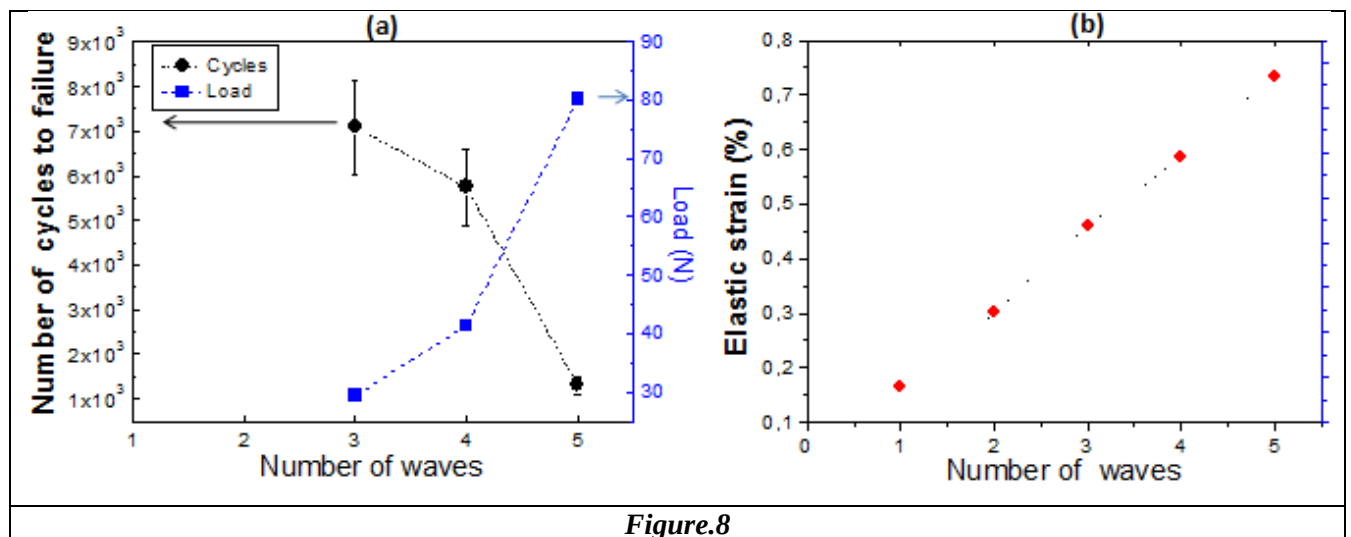


Figure.8

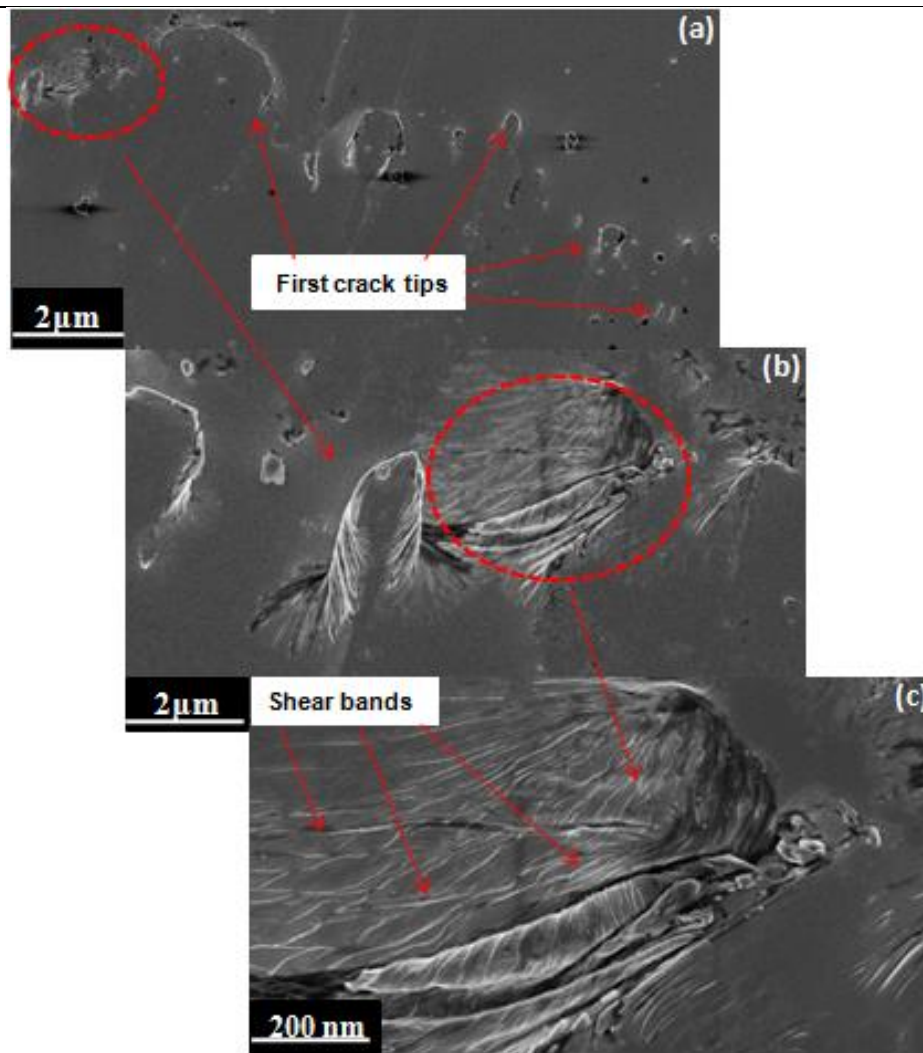


Figure.9



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