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# Novel micro-flat springs using the superior elastic properties of metallic glass foils

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## Abstract

A thin metallic glass foil of 100 mg massforming a sinusoidal arc behaves as non-conventional flat micro-spring withstanding loads $10^5$ times higher than its load. Upon a normal load applied on the top of the arc, the foil deforms elastically leading to sinusoidal wavy patterns of higher order. The lifespan of the novel spring is higher than conventional low cycle springs and can potentially be further improved by eliminating surface and edge preparation induced defects. This unique behaviour of metallic glass foils has the potential to revolutionize the field of springs and can be exploited for numerous applications.

**Key words:** Metallic glasses, wavy elastic response, buckling, flat micro springs, fatigue resistance.

# 1. Introduction

Springs are critical components in almost all modern technologies at various scales, from airplanes and trains to micro-electromechanical systems (MEMS) devices, with a primary role to store elastic energy and/or absorb mechanical shocks. The principal function of springs is based on the elastic deformation of the spring material (commonly steel, copper, or nickel alloys) under an applied load and the recovery of its initial shape after unloading [1]. In this respect, an ideal spring material would exhibit very high mechanical strength and elastic limit, much like the extraordinary properties of metallic glasses.

Unlike crystalline metals, metallic glasses lack a periodic lattice with slip planes on which mobile dislocations can cause plastic flow. Consequently, they show exceptionally high mechanical strengths up to 5 GPa and a wide elastic deformation range on the order of 2% before the onset of plastic deformation, about ten times higher than conventional crystalline metals. [2,3]. In addition, due to their amorphous structure and glassy nature, metallic glasses exhibit near net shape casting ability and excellent super-plastic formability in the super cooled liquid region, properties that make them attractive for various applications in different technological fields including in the biomedical, MEMS and NEMS (Micro- and Nano-Electro Mechanical Systems) sectors [4-7]. However, the bottleneck for their wider application is related to their limited ductility in tension. Nevertheless, this limitation does not impede the exploitation of their elastic properties in spring applications.

Recently, Aljerf et al [8] have shown that metallic glass foils can take complex shapes and wavy forms without thermal embrittlement through a rapid thermal annealing treatment (thermo-elastic processing) by controlling the structural relaxation kinetics. More recently, we have reported on a reversible elastic undulatory response of an arc-shaped metallic glass foil under normal load that can be utilized as an electromechanical switch [9].

Here, we explore the elastic deformation of metallic glass foils and the formation of sinusoidal wavy patterns for the design of a novel type of micro-flat spring with enhanced properties and functionality. The relation between load and displacement for the novel type of springs is overall exponential with discrete discontinuities at the position of multiplications of the sinusoidal arcs. The fatigue life of the novel springs was found to be better that of low cycle conventional springs.

## 2. Experimental details

Commercially available Fe-based metallic glass foils (Metglass, $Fe_{90.65}B_{3.9}Cr_{2.75}Si_{2.7}$ at%) with 19 μm thickness and 25 mm width and various lengths within the range 20 to 55 mm were elastically deformed to form sinusoidal arcs and fixed on a support.

The amorphous structure of the foils was verified by X-ray diffraction (XRD) using a RigakuGeigerflex diffractometer with Cu Ka radiation.

A normal load was applied on top of the arc surface using a Tinius Olsen H10kS compression machine. An Allied Vision Technologies Prosilica GX6600 CCD camera, equipped with an EXSIGMA macro lens was employed to film the loading and unloading cycles of the foils. Load-displacement curves were recorded for foils with a variety of initial arc dimensions with the main characteristic parameters being the foils' width, W, the horizontal boundaries' distance, L and the initial arc amplitude h, as shown in fig 1a. Cycling tests were carried out using a motorized device on metallic glass foils with dimensions of L=20 mm, h=5mm and W=25 mm. High-Resolution Scanning Electron Microscopy was employed to examine the foils after the cyclic loading tests using a ZEISS ULTRA 55 microscope equipped with a Field Emission Gun (FEG-SEM).

## 3. Results and discussion

### 3.1 Elastic wavy response of metallic glass spring-foils

When a normal load **F** is applied on the top of a metallic glass foil that has been elastically shaped to form a sinusoidal arc, fig 1a, the foil exhibits an extraordinary elastic/buckling behavior that can be utilized for developing a novel type of non-linear flat springs. Upon loading the foil deforms elastically; at specific values of load or displacement, the foil changes shape increasing the number of sinusoidal arcs from one initial arc successively to 2, 3, 4, 5 (and more) arcs, fig 1(b). When the load is released, the foil follows the opposite path reducing the number of formed arcs and gradually returning to its initial shape exhibiting a reversible wavy elastic response. At the moment of the formation of an additional arc-shaped undulation, all arcs have a perfect sinusoidal shape. With increasing load, the shape of the arcs becomes elastically distorted due to the elastic deformation of the foil, fig 1(c), until the load reaches a sufficient level to cause the formation of an additional arc. Figure 1(c) shows intermediate stages of the elastic deformation occurring between the formation of two and three sinusoidal undulations.

The relation between the applied load **F** and displacement ***x*** is quasi-exponential of the form: **F** $=\alpha\exp(\beta x)$, where $\alpha$ and $\beta$ are a geometry and materials related constants, with discrete discontinuities at specific values of load and displacement, as shown in fig 2(a).

These discontinuities are related to the change of the number of the formed sinusoidal arcs (arc-multiplication). At the intervals between the formation of wavy patterns with $n$ and $n$+1 sinusoidal arcs the applied load **F** increases quasi-linearly as a function of the displacement $x$. The slope between these intervals referred to as spring's rate (usually in N/mm units), defines the stiffness of a spring and is equivalent to the spring constant ***k*** for conventional linear springs. The metallic glass foils behave as non-linear flat springs with variable spring's rate ***k*** at different ranges of applied load **F** or displacement ***x*,** fig 2(b).

Furthermore, the elastic response of the metallic glass-foils to load and displacement can be easily tuned by modifying the geometry of the initial sinusoidal arc (amplitude h, length L, and width W) as well as by the choice of the metallic glass alloy (elastic modulus), fig 2(c). Thus an elastically arc-shaped metallic glass foil exhibits a wavy response under the application of normal load on the top of the arc, leading to the formation of mechanically induced sinusoidal waveforms of a higher order with the progressive increase of the applied load. The elastic response (load versus displacement) for each waveform can be seen as quasi-linear and differs from that of the waveform of either lower or higher order; in other words the spring's rate k (spring's stiffness) changes discretely at the moment (load or displacement) the $n^{th}$ waveform of the foil changes to the $n$+1 waveform. As a consequence, the same spring-foil exhibits different stiffness at different levels of applied load or different levels of displacement ($x$) allowing thus the fabrication of flat springs with multiple spring rates.

A closer look in fig 2(a), for example at the behavior of the L=40 mm foil, reveals that for the waveform with 5 arcs the load increases from about 5 N to 20 N for a displacement of 348μm. Even sharper increases in load are observed for higher order waveforms as for example for the L=50mm glassy foil with 7 arcs the load increases from about 21 N to 51 N for a compressive displacement of about 280 μm. Thus the metallic glass spring foils can operate at the micron scale when the desirable shape is given to the foil by the application of a pre-load. Alternatively, the glassy foil could be shaped to take a desirable waveform using stress-annealing without thermal embrittlement as described by Aljerf [8] or using electric current [10] as long as crystallization is avoided [11].

Therefore, this intrinsic wavy behavior of metallic glass ribbon with micrometric dimensions can be exploited for micro-flat spring applications with tunable spring's stiffness in micro-systems or micro-machines. In addition, such micro-flat spring can potentially be used as position or load sensors or electromechanical switch [9] since the multiplication of the undulations occurs at precisely determined displacements '***x***' which depends on the geometric characteristics of the spring (length L, amplitude h, width W, thickness d ) and the elastic constant of the glassy metal. The outstanding elastic/buckling behavior of metallic glass spring foils is also attractive for shock absorbing applications in devices or assemblies with enhanced performance [12].

Due to their higher specific strength, elasticity and the unique reversible wavy elastic response, the metallic glass spring foils have significantly reduced mass and lower compressive displacement when bearing similar loads with conventional spring materials with a ratio between the maximum attained loads and the spring's foil mass better than $10^3$ N/g. The functionality of metallic glass foils as a novel type of flat springs requires that the deformation remains at all stages within the elastic range (<<2 %) ensuring the reversibility of the mechanical response to loading conditions. This reversible elastic wavy response is a characteristic behavior only for metallic glass foils; conventional crystalline metallic foils were shown to fail when applied to similar loading conditions [9]. This occurs because crystalline metals bear about ten times lower elastic strains before yielding compared with the ~2 % elastic strain of metallic glasses. Thus, the metallic glass micro-flat springs are excellent candidates for applications in micro-or nano-electromechanical systems (MEMS or NEMS). Complex designs that will allow hybrid types of micro-springs to be developed are currently under consideration. The excellent wear and corrosion resistance of metallic glasses [13] may give additional advantages for applications as micro-flat springs in applications related to biomedical and marine systems.

### 3.2 Cycling lifetime

Fatigue constitutes a serious concern for most engineering applications, and metallic glasses have been observed, in some cases, to be prone to fatigue damage [14]. Although the fatigue mechanisms in amorphous metals are not well understood, it is believed that the underlying source of fatigue damage is related to defects such as gas pores or inclusions formed during casting or other fabrication methods [15].

In order to evaluate the effect of such defects in the life of the novel type of flat micro-springs proposed in this work, the behavior of the springs under cycling loading was studied using a motorized loading devised. Normal loads were applied on arc-shaped metallic glass foils leading to the multiplication of the arcs and then released allowing the foil to recover its initial sinusoidal arc shape with a frequency 0.27 Hz. Cycling tests were carried out on a 19 µm metallic glass foil with dimensions of L=20 mm, h=5mm and W=25 mm.

Fig 3(a) shows the maximum level of deformation that develops locally in the spring-foil at the moment of the formation of an additional arc. As it can be observed, the maximum deformation on the glassy foil remains well below the elastic limit of 2 % for metallic glasses, and the load reaches 80 N for the formation of the 5 arcs on the spring foil.

Fig. 3(b) shows the number of loading cycles that the metallic glass spring foil withstands before failure occurs. Here failure is defined as the formation of a fatigue crack or local plastic deformation that distorts the reversibility of the process; in other words, if the foil fails to take the perfect sinusoidal initial shape after the load is released it is considered a failure and the test is terminated. As it can be observed in fig 3(b), the lifetime of the glassy foils loaded up to 30 N forming 3 sinusoidal arcs was higher than 7 x $10^3$ cycles, whereas for the foils loaded up to 43 N forming 4 sinusoidal arcs the lifetime exceeds 5 x $10^3$ cycles, values that are better than the lifespan of low cycle conventional springs [16]. Taking into account that a thin spring foil of about 100 mg withstands a load of about 3 kg (30N) for more than 5 x $10^3$ cycles is indeed an impressive result. This can only be achieved due to the unique elastic properties of metallic glasses (~ 2% elastic limit, > 3 GPa strength for Fe-based based).

In order to understand the cause of the failure after the loading cycles, the foils were carefully examined with a high-resolution scanning electron microscope. Typical cracks formed after fatigue testing are shown in fig. 4. Two types of cracks were observed on the spring foils after the cyclic loading tests; one related to defects on the surface of the specimen (fig. 3c and 3d) and another related to specimen preparation (fig. 4). Casting defects are one of the important features for the initial stage of the fatigue damage [17]. The casting defects act as stress concentration sites inducing localized plastic deformation as manifested by the presence of shear bands around the defect, fig 3c and 3d. The presence of defects and shear bands can provoke the initiation of fatigue cracks leading to a brittle-type of fracture.

The second type of crack was always observed at the side edge of the foils specimen (fig. 4), starting from micro-notches created during the cutting process of the foils. In this case, the tip of the notch produces high-stress concentration thus serves as a preferential site for crack initiation. A close look at the point of crack initiation of fig 4a (circular image), may indicate that the primitive crack originated actually from a shear band. Firstly, the crack propagated in an almost straight line after initiation at the early stage perpendicularly to load application. Two noticeable path deflections then took place probably produced by the increased load with multiple arc formations. Close examination of fig 4 shows that the plastic zone at the crack tip is dominated by elongated shear bands (figures 4c to 4e) offering an easy path for the propagation of the fatigue cracks inside this well-developed shear band.

Thus the microscopical examination of the foils after cyclic loading clearly reveals that the formation of fatigue cracks and shear bands (observed as shear steps on the surface of the foils) occurs only near preparation induced defects (resulting from casting or cutting processes) on the surface or on the edges of the foils. No sign of plastic deformation was observed away from defects and fatigue cracks indicating that preparation induced defects are the main limiting parameter for the fatigue endurance of metallic glasses. It is believed that if casting defects are avoided during fabrication or reduced by surface treatment techniques the cycling life of the metallic glass foils can be considerably increased.

## 4. Conclusion

The exceptional mechanical properties of metallic glasses allow a thin foil elastically shaped to a sinusoidal arc form to exhibit a unique reversible elastic wavy response, which can be exploited for designing of micro-flat springs of a novel type. Under a normal load applied on the top of the sinusoidal arc, the foil deforms elastically leading to the successive formation of sinusoidal wavy patterns of higher order. The non-linear load versus displacement response allows the foil to act as a non-conventional spring with multiple equivalent spring constants at different ranges of applied load. The variation of the foil's dimensions give extensive possibilities for tuning the spring's properties and tailing its behavior based on the needs for specific applications. The fatigue lifespan of a 100 mg thin foil bearing cycling loads up to 30 N (~3 kg) was found to be higher than $5x10^3$ cycles, better than the conventional low cycle springs. Post surface treatment for eliminating surface casting defects is expected to increase significantly the lifespan of glassy foils in spring applications. The results presented throughout this work highlight the enormous potential for designing novel types of hybrid micro-flat springs utilizing the exceptional mechanical properties of metallic glass foils.

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**References**

[1] A. M. Wahl, Mechanical Springs Second edition, McGraw-Hill, New York, 1963.

[2] A. Inoue, B. Shen, H. Koshiba, H. Kato, A.R. Yavari, Nature Materials. 2 (2003) 661-663.

[3] A. R. Yavari, K. Georgarakis, W. J. Botta, A. Inoue, G. Vaughan, Phys Rev B. 82 (2010) 172-202

[4] A. Peker and W.L. Johnson, Appl. Phys. Lett. 63 (1993) 2342-2344.

[5] A .Inoue, Acta Mater. 48 (2000) 279-306.

[6] D.S. Nguyen, E. Halvorsen, G.U. Jensen and A. Vogl, J.Micromech.Microeng. 20 (2010) 125009.

[7] A.L Greer, Materials Today. 12 (2009) 14-22.

[8] M. Aljerf, K. Georgarakis, A.R. Yavari, Acta Mater. 59 (2011) 3817–3824.

[9] N.T. Panagiotopoulos, M.A. Yousfi, K. Georgarakis, A.R. Yavari, Materials and Design. 90 (2016) 1110–1114.

[10] W.J. Botta F, A.M. Jorge, M.J. Rodrigues, C.S. Kiminami, C. Bolfarini, M.F. de Oliveira, A.R. Yavari, Journal of Metastable and Nanocrystalline Materials. 15-16 (2003) 11-16.

[11] K. Georgarakis, D. Dudina, V.I. Mali, A.G. Anisimov, N.V. Bulina, A.M. Jorge Jr, A.R. Yavari, Appl. Phys. A. 120 (2015) 1565–1572

[12] T. Frenzel, C. Findeisen, M. Kadic, P. Gumbsch, M. Wegener, Adv. Mater. 28 (2016) 5865-5870.

[13] S.J. Pang, T. Zhang, K. Asami, A. Inoue, Acta Mater. 50 (2002) 489–497.

[14] C.A. Schuh, T.C. Hufnagel and U. Ramamurty, Acta Mater. 55 (2007) 4067.

[15] Y. Yokoyama, D. G. Harlow. P.K. Liaw, A. Inoue, Met Mat Trans A. 41A (2010) 1780-1786.

[16] D.M. Li, K.W. Kim, C.S. Lee, Int. J. Fatigue. 19 (1997) 607-612.

[17] 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, Intermetallics.13 (2005) 429–435.

## Figure Captions

*Figure.1. The concept of a metallic glass flat spring: a) geometrical characteristics of the initial elastically shaped foil, b) wavy elastic response under loading with the formation of up to 5 sinusoidal arcs, and c) elastic deformation between the events of formation of two (top picture) and three sinusoidal arcs (bottom picture).*

*Figure.2. (a) Evolution of correspondent normal applied load* ***F*** *versus displacement* ***x*** *for different boundary conditions of L, b) spring's rate* ***k*** *as a function of the number of sinusoidal arcs for various boundary conditions of L, and c) level of applied loads as a function of the number of sinusoidal arcs.*

*Figure.3. (a) Maximum strain level developed on the spring during the formation of additional arcs upon loading and the corresponding loads, (b) Lifetime of the metallic glass spring foils during fatigue tests and the corresponding load as a function of the maximum number of formed arcs, (c) and (d) SEM images after first failure (4 waves are used as a spring). These images show many shear bands around surface defect on the ribbon.*

*Figure.4. SEM images after first failure (spring foils forming up to 4 sinusoidal arcs). These images show that the crack initiation was induced by defects produced during sample preparation and the formation of many shear bands around the tip of the crack.*

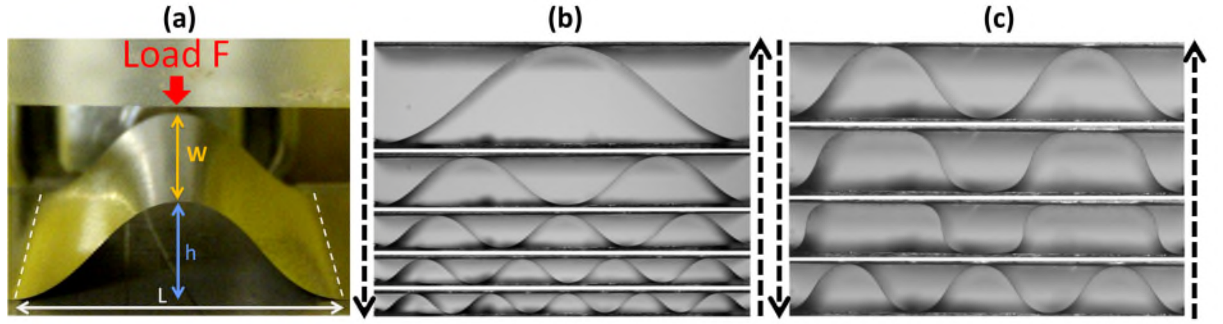


*Figure.1.*

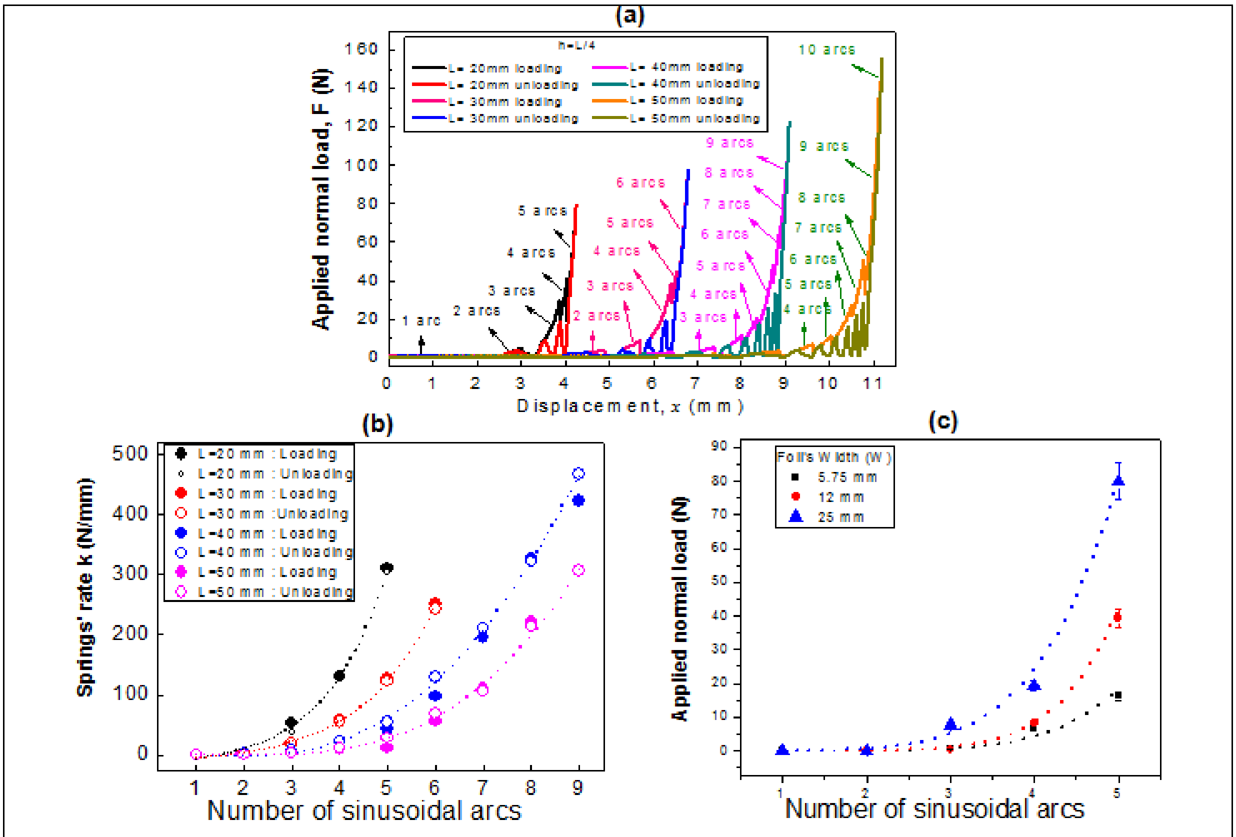
(a)
h=L/4
L= 20mm loading
L= 20mm unloading
L= 30mm loading
L= 30mm unloading
L= 40mm loading
L= 40mm unloading
L= 50mm loading
L= 50mm unloading
Applied normal load, F (N)
Displacement, x (mm)
(b)
Springs' rate k (N/mm)
Number of sinusoidal arcs
(c)
Foil's Width (W)
5.75 mm
12 mm
25 mm
Applied normal load (N)
Number of sinusoidal arcs

***Figure.2.***

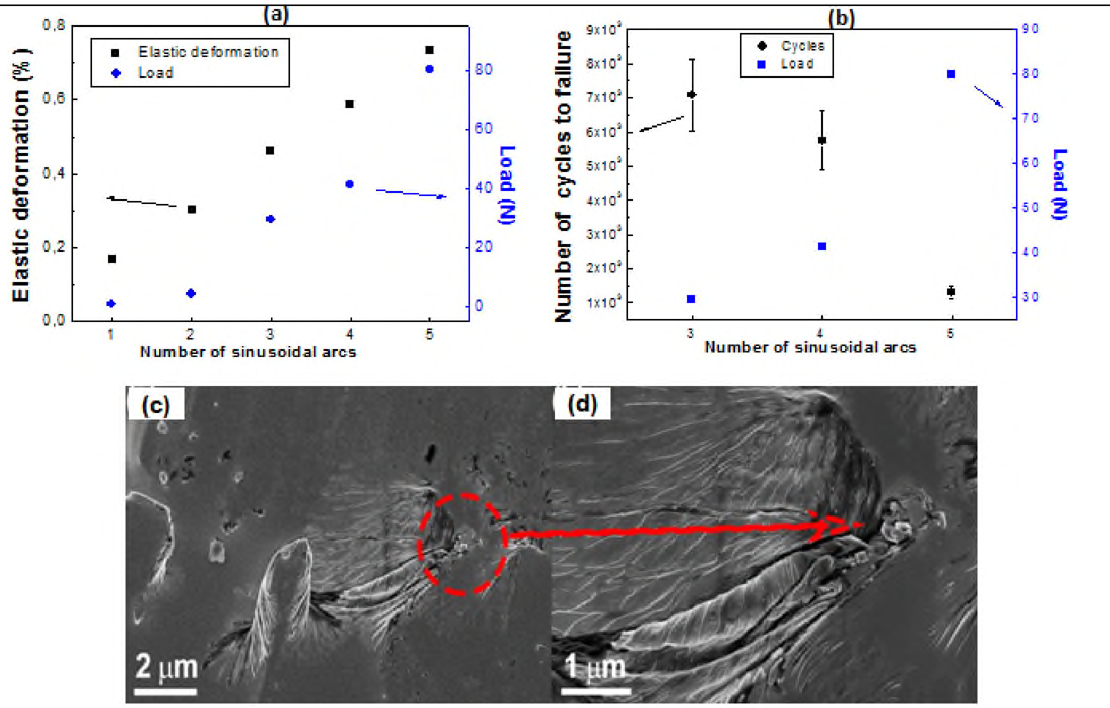
(a)
Elastic deformation (%)
Elastic deformation
Load
Load (N)
Number of sinusoidal arcs
(b)
Number of cycles to failure
Cycles
Load
Load (N)
Number of sinusoidal arcs
(c)
2 μm
(d)
1 μm

*Figure.3.*

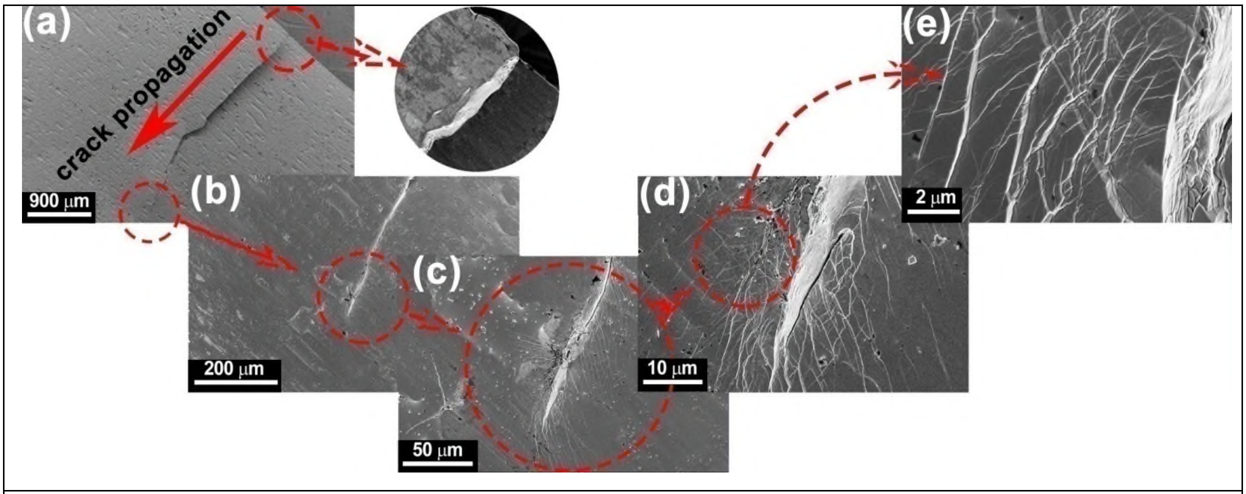


***Figure.4.***

# Novel micro-flat springs using the superior elastic properties of metallic glass foils

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