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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 mass forming 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 behavior of metallic glass foils has the potential to revolutionize the field of springs and can be exploited for numerous applications.

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

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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 Rigaku Geigerflex 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 = 5 mm 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. Fig. 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: $\mathbf{F} = \alpha \exp(\beta x)$, where α and β 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 nth 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 348 μm. Even sharper increases in load are observed for higher order waveforms as for example for the L = 50 mm 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 ($\ll$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

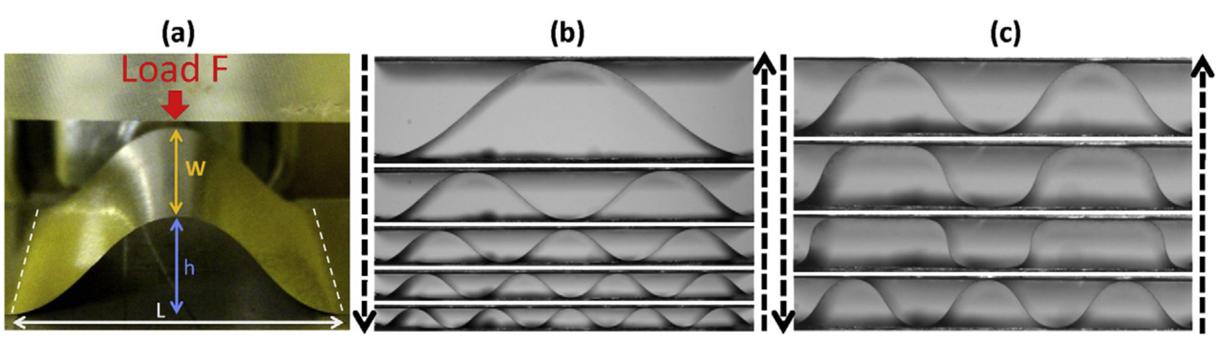

Fig. 1. The concept of a metallic glass flat spring: a) geometrical characteristics of the initial elastically shaped foil, b) wavy elastic response under loading with the formation of up to 5 sinusoidal arcs, and c) elastic deformation between the events of formation of two (top picture) and three sinusoidal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