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Development of a high-resolution micro-torsion tester for measuring the shear modulus of metallic glass fibers

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Abstract

A high-resolution micro-torsion tester is developed based on electromagnetism, and the shear modulus of metallic glass fiber ($Pd_{40}Cu_{30}Ni_{10}P_{20}$) is measured using this tester. The torque is measured by a coil-magnet component and the rotation angle is measured by an inductive angular transducer. The calibration results show that the torque capacity of this tester is 1.1×10^{-3} N m with resolution of 3×10^{-8} N m and the rotation angle capacity is 90° with a resolution of 0.01°. A set of metallic glass fibers, with diameter of about 90 μm, are tested using this tester. The average shear modulus is obtained as 20.2 GPa (±6%).

Keywords: micro-scale, torsion, metallic glass fiber, shear modulus

(Some figures may appear in colour only in the online journal)

1. Introduction

Metallic glass has found important applications as magnetic core or reinforcement added to other materials [1–3] since it was created as a member of the amorphous materials family in 1960 [4]. It has become more evident that the elastic modulus plays a very important role in the formation and properties of non-crystalline matter [5]. Until now, the shear modulus of metallic glass has usually been measured by the electromagnetic acoustic transformation method [6, 7]. A direct torsion test has rarely been reported, especially for metallic glass fibers. The main reason is that, for micro-scale samples with diameter of 0.1 mm or less, the test torque is usually of the order of 10^{-4} N m or even less. Commercial torsion testing machines, such as MTS Bionix EM torsion test system and INSTRON MT Series Torsion Tester, etc do not have enough resolution for these tests.

Moreover, so far, relatively few studies have been reported on the torsion techniques for micro-scale samples. The most important experiment was performed by Fleck *et al* [8] on polycrystalline copper wires in 1994. Several glass fibers with different diameters were employed as the torque sensors, which were calibrated by using a deadweight and pulley arrangement. However, some important experimental details, such as the torque calibration process and results, were not presented. In 2010, Lu and Song [9] replicated the torsion test on copper wires with the aid of the MTS 858 testing machine. Their work basically followed the concept in Fleck's paper [8] by hand-building a rotation sensor and using a glass fiber for small torque measurement. The torque calibration process and results were described in detail. It is a significant promotion to the torsion technique because more experiment details were reported. However, it is a pity that the torque calibration data scatter is up to 17% because the capacity of a standard sensor is much greater (about three orders of magnitude) than the torque range of the glass fiber sensor. In 2011, Walter and Kraft [10] developed a torsion technique based on an atomic force microscope (AFM) with the aid of a Zwick Z 2.5 testing machine. Two AFM tips were employed for the torque measurement through a rigid cross-beam bonded to the

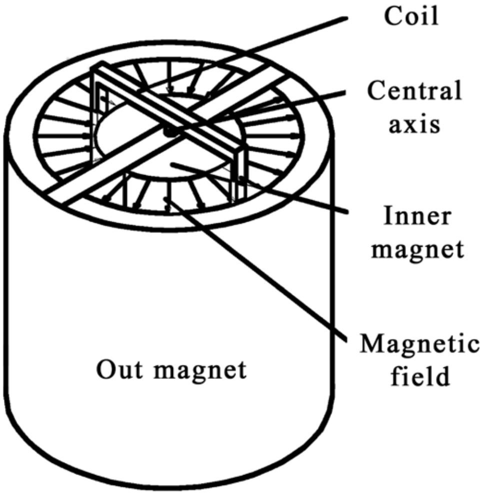

Figure 1. Schematic diagram of the coil-magnet actuator.

sample. A 50 μm diameter tungsten fiber was used to calibrate the AFM-tip sensor by assuming that the tungsten fiber is an isotropic material with known shear modulus. This technique has a good torque resolution, but the vertical misalignment and the roughness of cross-beam may lead to an obvious data fluctuation. In 2013, Liu *et al* [11] reported a high-resolution torsion technique based on an automated torsion balance. The torque is measured by a tungsten fiber, whose torsion constant was calibrated by means of a torsional resonance method. It is a smart method, but the nonlinear error of the relationship between torque and rotation deformation of tungsten fiber cannot be presented in detail.

It is not hard to find that the mainstream technology of torque measurement has the same concept, namely, a sensitive elastic element is employed as the torque sensor. However, it is difficult to make a compromise between the wide torque span and perfect resolution because the torque scales with the cube of the sample's diameter. For example, both Fleck [8] and Lu [9] had to replace different size glass fibers for different size samples in order to acquire sufficient torque resolution. Moreover, the torque calibration methods were different from each other, which made the comparability and traceability of the results worse.

In this work, a novel micro-torsion tester based on electromagnetism, with characteristics of perfect torque resolution and linearity, was developed to perform the torsion tests on metallic glass fibers ($Pd_{40}Cu_{30}Ni_{10}P_{20}$) with diameter of about 90 μm. The shear modulus was obtained for the first time by using a torsion test.

2. Micro-torsion tester

2.1. Design concept

The novel micro-torsion tester is developed based on electromagnetism, in which a coil placed in a radial magnetic field is employed for actuation and torque measurement. The schematic diagram of the coil-magnet component is illustrated in figure 1. There exists a radial magnetic field between the concentrically located inner and outer magnets. When current passes through the coil, the coil is actuated and rotates around the central axis. The actuating raw torque, produced by the Ampere force, can be easily measured according to the following formula,

$$T_{\text{raw}} = Fw = BIlw = CI \tag{1}$$

where F is the Ampere force produced by one side of the coil, w is the width of the coil frame, B is the magnetic flux density, I is the value of the current in wire and l is the total length of wire immersed in the magnetic field. If B is constant, C will be a constant, which can be determined through the prior calibration work. Consequently, the raw torque T_{raw} can be easily measured by recording the current I.

In order to measure the rotation angle of the coil θ_{raw} without any influence on the torque measurement, an inductive angular transducer is employed. It is a non-contact measurement technology without any friction on the coil.

2.2. Mechanical model

The structure of the micro-torsion tester is illustrated in figure 2(*a*). However, some problems are introduced because the wire must lead to a power supply and the coil must be supported by a bearing. Subsequently, the true torque on sample is influenced by the stiffness of the lead wire and the friction of the bearing, and the rotation angle is influenced by the stiffness of the body frame. In order to illustrate these influences, the mechanical model of the tester is shown in figure 2(*b*), with all damping ignored in static tests.

The true torque T applied on the sample and the true rotation angle of sample θ can be calculated as

$$T = T_{\text{raw}} - T_l - f = T_{\text{raw}} - K_l \times \theta_{\text{raw}} - f \tag{2}$$

$$\theta = \theta_{\text{raw}} - \theta_f = \theta_{\text{raw}} - \frac{T}{K_f} \tag{3}$$

where K_l is the stiffness of the lead wire, f is the friction of the bearing and K_f the stiffness of the body frame.

In order to obtain the true torque and rotation angle of the sample according to equations (2) and (3), a series of calibrations were performed to precisely determine the influence factors.

2.3. Calibration

The calibration of the torque was performed with the aid of a Sartorius BSA124S-CW electronic balance, with a resolution of 0.1 mg. The micro-torsion tester was placed horizontally to drive a slim and rigid probe to press the balance pan. The change in reading of the balance was transformed to torque by taking the force arm into account. Consequently the relationship between torque and current was obtained according to the current in the coil and the change in reading of the balance.

The relationships of the torque and current were calibrated, as shown in figure 3. A perfect linear relationship was observed between the torque and the current, with nonlinearity of about 1% throughout the full torque capacity.

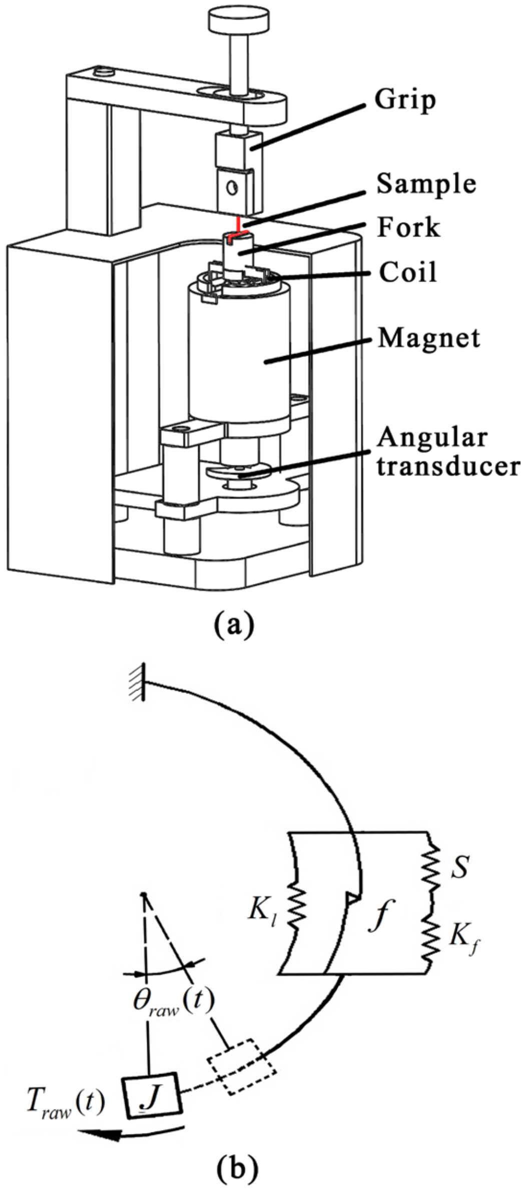

Figure 2. Illustration of the micro-torsion tester. (*a*) Schematic diagram, (*b*) mechanical model. J is the rotational inertia of the movable mass, S the torsional stiffness of the sample, K_l the torsional stiffness of the lead wire, f the friction torque of the bearing and K_f the torsional stiffness of the body frame.

The stiffness of the lead wire was calibrated by rotating the coil without any external load. The average stiffness is 3.3×10^{-8} N m deg^{-1} with nonlinearity of less than 3%. The friction torque of the bearing is nearly a constant of 2.5×10^{-6} N m at typical rotation speed. The stiffness of the body frame is 2.0×10^{-3} N m deg^{-1}.

The torque capacity is 1.1×10^{-3} N m, which is limited by the allowable current in the coil. The torque resolution is 3×10^{-8} N m and the rotation angle resolution is 0.01°. The main technical parameters are listed in table 1.

3. Torsion tests of metallic glass fibers

A set of metallic glass fibers ($Pd_{40}Cu_{30}Ni_{10}P_{20}$) with diameter of about 90 μm, made using the method reported in [12], were tested using the micro-torsion tester developed in this paper. The exact diameter of each fiber was measured using a scanning electron microscope (SEM), as shown in figure 4.

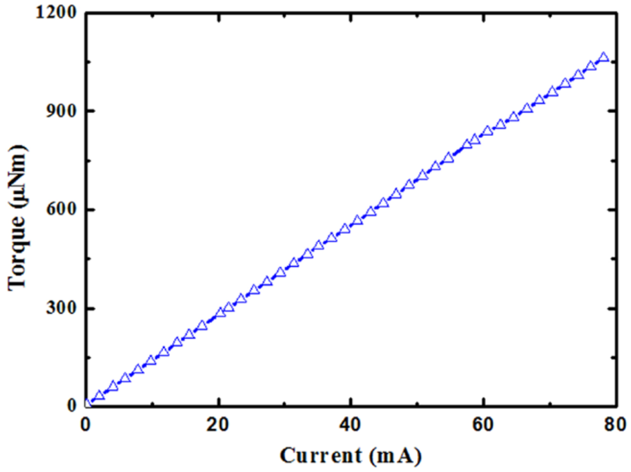

Figure 3. Relationship between the torque and current throughout the full torque capacity.

Table 1. Main technical parameters of the micro-torsion tester.

Technical parameters		Value
Torque	Capacity	1.1×10^{-3} N m
	Resolution	3×10^{-8} N m
Rotation angle	Capacity	90°
	Resolution	0.01°

The metallic glass fiber was glued on a paper-card to avoid accidental damage. One end of the paper-card sample was firmly clamped on the upper grip. The other end, glued with a rigid rod, was placed into the fork of the movable grip. The gauge length was about 5 mm, measured separately after the sample was clamped. Afterwards, the paper-card was cut off and a small torque was gradually applied on the fiber sample by increasing the current in the coil. The strain rate at the fiber's surface was controlled to be of the order of 10^{-4} s^{-1}. The raw torque and the rotation angle of the coil were recorded automatically. The true torque and the rotation angle of sample were then obtained according to equations (2) and (3).

The shear stress at surface τ and shear strain at surface γ can be calculated according to the following equations:

$$\tau = \frac{16T}{\pi D^3} \tag{4}$$

$$\gamma = \frac{\theta D}{2L} \tag{5}$$

where D and L are the diameter and gauge length of the fiber sample respectively. It should be noted that equation (4) is only for pure elastic deformation and equation (5) is only valid for small twist.

The curves of shear stress–shear strain at the surface of three samples present clear elastic behavior, as shown in figure 5. The average shear modulus is 20.2 GPa (±6%). It should be noted that the samples were not twisted off because of the limit of the rotation angle capacity.

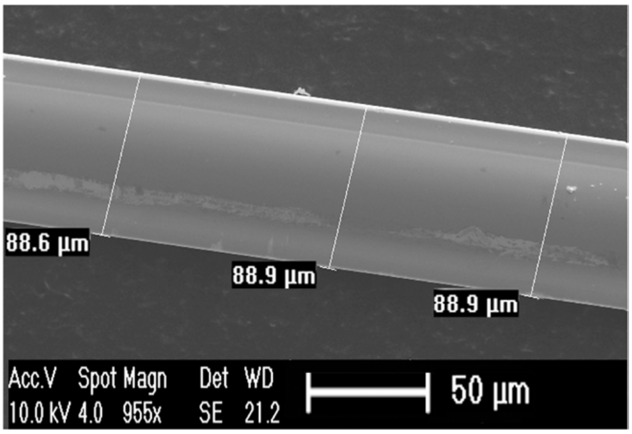

Figure 4. SEM photo of the metallic glass fiber with diameter of about 90 μm.

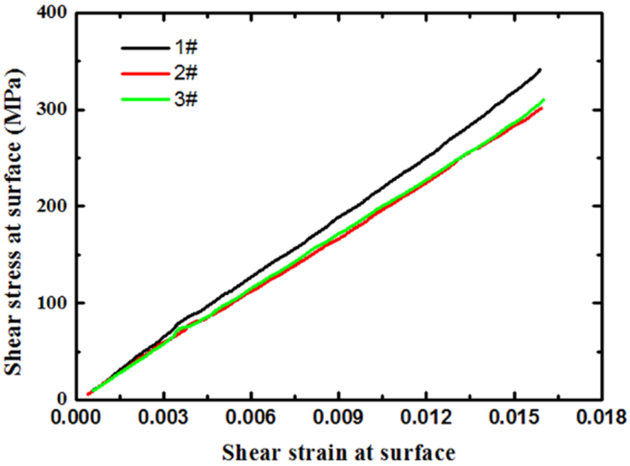

Figure 5. Relationship between the shear stress and shear strain at the surface of the metallic glass fibers. The average shear modulus is 20.2 GPa (±6%).

4. Summary

In this paper, a micro-torsion tester was developed based on electromagnetism, in which a coil-magnet component was employed for actuation and torque measurement. An inductive angular transducer was employed for measuring the rotation angle. The calibration results showed that the torque capacity is 1.1×10^{-3} N m with a resolution of 3×10^{-8} N m. The rotation angle capacity is 90° with a resolution of 0.01°.

A set of metallic glass fibers with diameter of about 90 μm was tested using this micro-torsion tester. The curves of shear stress versus shear strain at the surface show clear elastic behavior, with average shear modulus of 20.2 GPa (±6%).

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References

[1] Wang W H, Dong C and Shek C H 2004 Bulk metallic glasses *Mater. Sci. Eng. R.* **44** 45–89
[2] Nielsen O V, Petersen J R, Fernandez A, Hernando B, Spisak P, Primdahl F and Moser N 1991 Analysis of a fluxgate magnetometer based on metallic-glass sensors *Meas. Sci. Technol.* **2** 435–40
[3] Helseth L E 2013 Optical fibre spectrometer combined with a magnetic resonance sensor for multiple depth monitoring *Meas. Sci. Technol.* **24** 085605
[4] Klement W, Willens R H and Duwez P 1960 Non-crystalline sructure in solidified gold–silicon alloys *Nature* **187** 869–70
[5] Makarov A S, Khonik V A, Mitrofanov Y P, Granato A V and Joncich D M 2013 Determination of the susceptibility of the shear modulus to the defect concentration in a metallic glass *J. Non-Cryst. Solids* **370** 18–20
[6] Zhang B, Bai H Y, Wang R J and Wang W H 2007 Shear modulus as a dominant parameter in glass transitions: ultrasonic measurement of the temperature dependence of elastic properties of glasses *Phys. Rev.* B **76** 012201
[7] Makarov A S, Khonik V A, Wilde G, Mitrofanov Y P and Khonik S V 2014 'Defect'-induced heat flow and shear modulus relaxation in a metallic glass *Intermetallics* **44** 106–9
[8] Fleck N A, Muller G M, Ashby M F and Hutchinson J W 1994 Strain gradient plasticity—theory and experiment *Acta Metall. Mater.* **42** 475–87
[9] Lu W Y and Song B 2011 Quasi-static torsion characterization of micro-diameter copper wires *Exp. Mech.* **51** 729–37
[10] Walter M and Kraft O 2011 A new method to measure torsion moments on small-scaled specimens *Rev. Sci. Instrum.* **82** 035109
[11] Liu D B, He Y M, Dunstan D J, Zhang B, Gan Z P, Hu P and Ding H M 2013 Toward a further understanding of size effects in the torsion of thin metal wires: an experimental and theoretical assessment *Int. J. Plasticity* **41** 30–52
[12] Yi J, Xia X X, Zhao D Q, Pan M X, Bai H Y and Wang W H 2010 Micro and nano scale metallic glass fibres *Adv. Eng. Mater.* **12** 1117–22