沈積氧化銦錫薄膜於聚對苯二甲酸乙二醇酯基板在疲勞測試下之變形研究

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摘 要

近幾年來，軟性電子元件具有靈活性和高度整合性的優點而備受關注。該技術已朝著人性化技術的方向發展並考慮了方便使用，便利攜帶，感知，穿戴以及與周圍環境的智能通訊之相關應用。可撓性是軟性電子元件具有的機械特性。因此，分析軟性基板的變形將會是可拉伸電子裝置是一項挑戰。在本研究中，提出了一種在不同的扭轉角度和疲勞試驗條件下對聚對苯二甲酸乙二酯基板的扭轉行為進行分析的方法，探討了不同長寬比例和材質的基板之變形。另外，在本研究中，使用光纖光柵傳感器來測量聚對苯二甲酸乙二酯基板的表面應變。最後，從動態疲勞測試下，探討不同基板上的應變與測試週期數之間的關係並判斷基板是否產生永久變形。

關鍵詞：軟性電子、疲勞測試、氧化銦錫薄膜、聚對苯二甲酸乙二醇酯基板、扭轉

Investigation on Deformation of Indium Tin Oxide Coated Polyethylene Terephthalate Substrates under Fatigue Test

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Abstract

Flexible electronic devices have attracted great attention due to their advantages of both flexibility and multi-level integration in recent years. The technology has been progressing towards human-friendly technology which considers ease of use, portability, human sensibility, wearing sensation, and smart communication with surrounding environments. Mechanical flexibility is the remarkable characteristic of flexible electronic devices. It is therefore a challenge to analyze the deformation of polyethylene terephthalate (PET) substrates subjected by pure torsion suitable for stretchable device applications. In this research, an analytical method for the twisting behavior of PET substrates is proposed under different twisting angles and fatigue test. Different screen ratios and materials of PET substrates were compared, respectively. In addition, the fiber grating sensor was used to measure the surface strain of the PET substrates in this experiment. Finally, experimental results show the relationship between the strain and number of test cycle on the different substrates during dynamic fatigue test to determine the permanent deformation.

Keywords: Flexible Electronics, Fatigue Test, Indium tin oxide, Polyethylene terephthalate, Twisting

Received: Sep. 25, 2020; first revised: Nov. 18, 2020, accepted: Nov. 2020.
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Ⅰ. Introduction

Electronic devices are usually made and processed on glass substrates (TVs, PC computers, portable computers, mobiles, etc.). Flexible electronics is one of the most promising technologies for next generation through the implementation of soft substrates. The industry trend of the rise of flexible electronics has become increasingly clear, and products such as displays, lighting, solar cells, and sensors have gradually moved from the laboratory to the market [1–2]. This technology also leads to the creation of innovative products that can be produced more human-friendly and cheaply. The flexibility in flexible electronic devices depends on the soft substrates. The substrate can be applied to flexible electronic textiles, smart labels and array sensors because they are lightweight, cost effective and deformable. In general, glass, metal foil and plastic materials can be applied to soft substrates. Among them, plastic is the key material of choice due to its good performance and properties in mechanical, optical and chemical fields. Besides, it is cheap and can be manufactured by using roll-to-roll processes.

Flexible electronics are fabricated by adding a suitable layer of thin film material to a transparent plastic substrate and can be stretched, compressed, bent, and deformed into arbitrary shapes without mechanical or electrical failure in circuits. During the manufacturing process, changes in temperature cause residual stress in the film which affects its quality and yield. Typically, the film stress is measured from the change of curvature of substrate before and after deposition, and then uses the Stoney equation to calculate the quantity of the stress [3]. Many experimental methods for residual stress by using Stoney equation are developed [4–5]. Besides, some modifications for Stoney equation are investigated for different application [6–7]. In addition, the tensile and bending test for film deposition on the polymer substrates is worth studying. The crack effect of residual stress for glass film deposited on a polymer substrates and optical behavior were investigated under the tensile test [8–10]. As for the discussion of soft substrates under bending, analytical equations and measurement mechanism were proposed to analyze the mechanical properties of the soft substrates under bending due to the effect of external force and temperature [11–13].

Since mechanical flexibility is the remarkable characteristic of soft electronic devices, the dynamic analysis of soft substrates caused by pure twisting moment will contribute to its design. However, many studies usually focus on dynamic analysis like tensile and bending test for soft substrates or film deposition on soft substrates, with little attention paid to twisting test. [14–16]. In fact, the behavior of twist in daily use is more frequent than stretching and bending, and the former is more easily to crack and damage. Hence, this study aims for in-plane deformation and strain analysis of soft substrates subjected to pure torsion under fatigue test. In this experiment, the fiber grating sensor is adapted for strain measurement of polyethylene terephthalate (PET) substrates under twisting test. Deformation behaviors of indium tin oxide (ITO) coated PET substrates under different twisting angles are investigated. In addition, different aspect ratios are discussed under static and dynamic twisting fatigue test for the PET substrates and ITO coated PET substrates. These results serve as guideline to predict the response of flexible electronics and are useful for device design.

II. Theoretical Study

A soft substrate with thickness h is composed of length a and width b subjected to pure twisting moment with a corner point fixed as shown in Fig. 1. The deflection w, out-of-plane displacement on the soft substrate, satisfying the geometric boundary conditions is assumed as [17]

$$w = A(x-a)(y-b) \tag{1}$$

where A is the deflection amplitude depending on twisting moment and the boundary conditions of the soft substrate with bending moment free under twisting moment are thus given as

$$M_{x=0} = M_{x=a} = M_{y=0} = M_{y=b} = 0 \tag{2}$$

$$w(0,0) = 0 \tag{3}$$

the strain components of the soft substrate can be derived as

$$\varepsilon_x = \frac{\partial u}{\partial x} - z\frac{\partial^2 w}{\partial x^2} + \frac{1}{2}\left(\frac{\partial w}{\partial x}\right)^2 \tag{4}$$

$$\varepsilon_y = \frac{\partial \upsilon}{\partial y} - z\frac{\partial^2 w}{\partial y^2} + \frac{1}{2}\left(\frac{\partial w}{\partial y}\right)^2 \tag{5}$$

$$\varepsilon_{xy} = \frac{1}{2}\left(\frac{\partial \upsilon}{\partial x} + \frac{\partial u}{\partial y} - 2z\frac{\partial^2 w}{\partial x \partial y} + \frac{\partial w}{\partial x}\frac{\partial w}{\partial y}\right) \tag{6}$$

where ε_x and ε_y are the normal strain components in the x- and y-directions, respectively, and ε_{xy} is the shear strain component in the x-y plane. In addition, u and υ are the initial mid-plane deformations in the x- and y-directions, respectively. In this research, the initial mid-plane deformations are ignored in order to avoid the substrate membrane forces. Figures 2(a) and (b) show schematic diagram and photo of soft substrate subjected to pure torsion. A fiber grating sensor (FBG) was attached to the middle of the substrate surface relative to the x axis with an orientation angle of θ=45° (diagonal line of the substrate). According to strain transformation formula [16] and Eqs. (4)–(6), the stains of the fiber grating sensor can be calculated as

$$\varepsilon = \varepsilon_x \cos^2\theta + \varepsilon_y \sin^2\theta + 2\varepsilon_{xy}\sin\theta\cos\theta = \frac{1}{4}\left[(x-a)^2 + (y-b)^2 + 2(x-a)(y-b)\right]A^2 \tag{7}$$

After measuring strain ε on the surface of the substrate, the deflection amplitude *A* need to be calculated by using Eq. (7). Then by substituting *A* into Eq. (1), The substrate deflection w can be obtained.

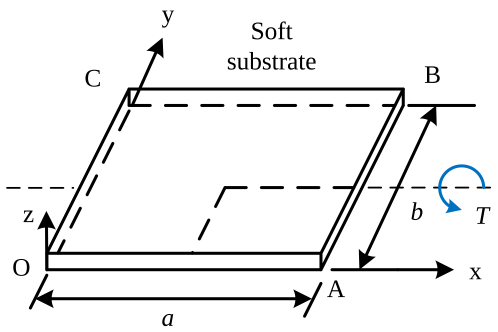
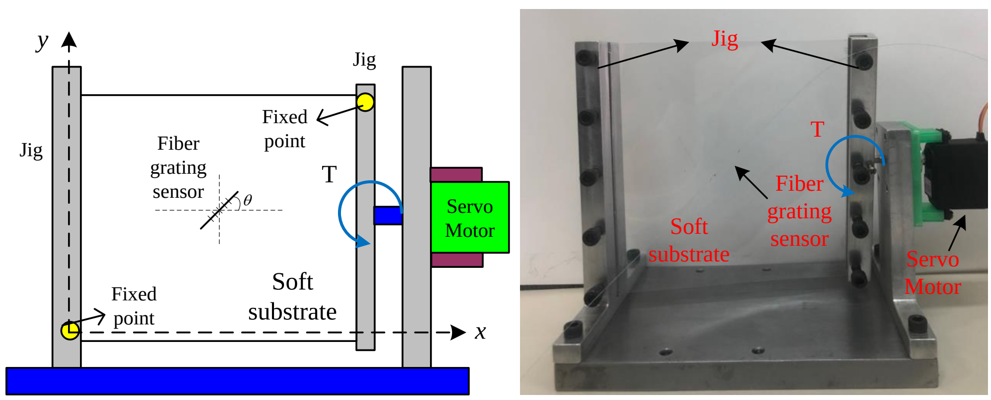


Fig. 1 Schematic diagram of theoretical model



(a) Schematic diagram (b) Photo of soft substrate subjected to pure torsion

Fig. 2 Schematic diagram and photo of soft substrate subjected to pure torsion

III. Experimental Study

In this research, the soft substrates like PET substrates and ITO coated PET substrates are used for dynamic twisting tests by an electric servo motor. The PET substrate is clamped in one corner while the other side is attached to a SmartMotor-made servo motor that exerts pure torsional loading by a computer. In computer control, the angle mode of the electric motor is used. The sample position has to be reset whenever inputting twisting angle due to easy deformation of the PET substrates by itself. Figure 3 and 4 show the schematic diagram and photo of experimental setup. In this measurement, we apply a fiber Bragg grating to detect the surface strain of the soft substrates. A broadband light source in the conventional wavelength band (C-band) between 1525 and 1565 nm is adapted in the experiment. The broad band light beam incidents into a fiber coupler and then split into a FBG stuck on the surface of PET substrates. A narrowband spectral component satisfied the following condition at the Bragg wavelength λ is reflected by the grating.

$$\lambda = 2n\Lambda \qquad (8)$$

with n the index of refraction and Λ the period of the index of refraction variation of the FBG. Due to the temperature and strain dependence of the parameters n and Λ, the reflected Bragg wavelength will also change as function of temperature or strain. By detecting the shift of Bragg wavelength from optical spectrum analyzer (OSA) of 0.1 nm resolution, the surface strains caused by external pure torsional loading can be found to be [18]

$$\frac{\Delta\lambda}{\lambda} = (1 - p_e)\varepsilon = 0.76\varepsilon \qquad (9)$$

where Δλ is the shift of Bragg wavelength and p_e is the photoelastic constant of the PET substrate.

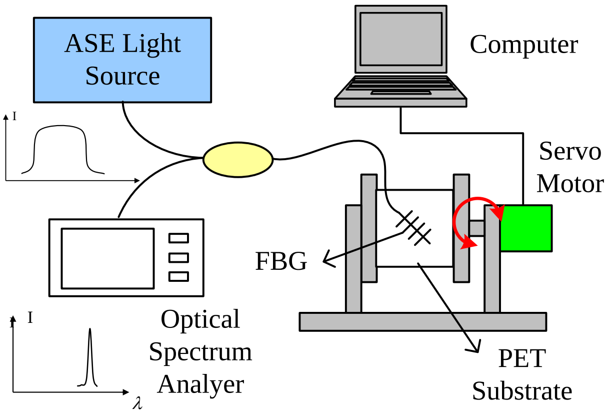


Fig. 3 Schematic diagram of experimental setup

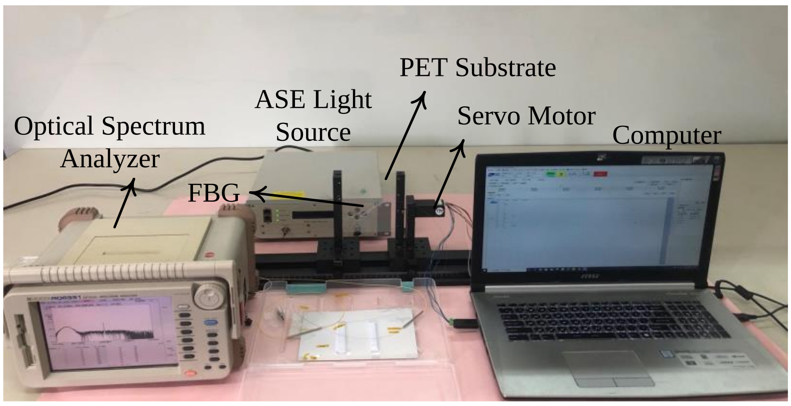


Fig. 4 Photo of experimental setup

IV. Experimental Results and Discussion

In this research, the optical fiber grating with Bragg center wavelength 1550 nm is proposed to measure the surface strain of soft substrates subjected to pure torsion. Two soft substrates, 175 and 125 μm thick polyethylene terephthalate (PET) substrates, are selected in our experiment to measurement the surface strain during dynamic twisting test. Table 1 shows the dimensional sizes and materials of selected PET samples. Two jigs are used to hold the PET substrate subjected to torque. The left-hand jig is fixed while the right-hand jig is attached to a rotational motor that exerts twisting moment. The PET substrate is fixed at two corners of the diagonal in order to avoid the presence of the substrate membrane force. Strains are measured with a FBG stuck on the middle surface of PET substrates with 45-degree orientational angle. The curve trend is stable are within the range of torsional angles from 0 to 30 degrees due to in-plane deformation induced over 30 degrees [25]. Accordingly, the PET substrates are exerted by external pure torsion under different periodic cycles for dynamic fatigue test. In this experiment, deformation of the selected samples is measured by fiber grating system per 1000 periodic cycles (0 – 20 – -20 – 0 degree) for daily and normal use. The maximum testing cycle is up to 20000. Since most of the test samples will not permanently deform in less than 5,000 cycle times, the changes in the measured strain values are within a reasonable range. Therefore, an empirical formula for average strain deviation can be proposed as follows

$$Average\ strain\ deviation = \left| \frac{\varepsilon - \varepsilon_{ave\,(1000\sim5000)}}{\varepsilon_{ave\,(1000\sim5000)}} \right| \quad (10)$$

Figures 4(a) and (b) show dynamic experimental results for PET substrate with dimensions of 10 cm x 10 cm x 175 μm and 10 cm x 10 cm x 125 μm (sample #1 and #2), respectively. It shows that PET substrates with larger thickness can withstand higher number of cycles under dynamic twisting tests (deviation ≤ 1). In addition, average strain deviations of different screen ratios (substrate length/width) are compared with the same twisting angle under dynamic fatigue test.

Figure 4(c) shows the relationship between surface strain and twisting cycle number for the 125 μm PET substrate of length 15 cm and width 10 cm corresponding to screen size ratio=1.5. Experimental results show that larger screen ratio (length/width =1.5) is not easier to deform and more stable than lower one (length/width =1) under twisting fatigue test due to its smaller strain value under the same twisting angle. Figure 4(d) shows the relationship between surface strain and twisting cycle number for the 100 nm ITO-coated PET substrate with dimensions 15 cm x 10 cm x 125 μm corresponding to screen size ratio=1.5. It is obvious to see critical cycles to determine permanent deformation above 6000 cycles for ITO-coated PET substrate under the same aspect ratio. The reason for the production of critical cycles of sample 1, 2 and 3 may come from the permanent deformation of the PET substrate, and sample 4 may come from the delamination, buckling, bulging or peeling between the ITO film and the substrate.

Table 1 Dimension and material of selected PET sample

Sample No.	Dimension (length x width x thickness) and material
1	PET (10 cm x 10 cm x 175 μm)
2	PET (10 cm x 10 cm x 125 μm)
3	PET (15 cm x 10 cm x 125 μm)
4	PET (10 cm x 10 cm x 125 μm) + ITO 100 nm

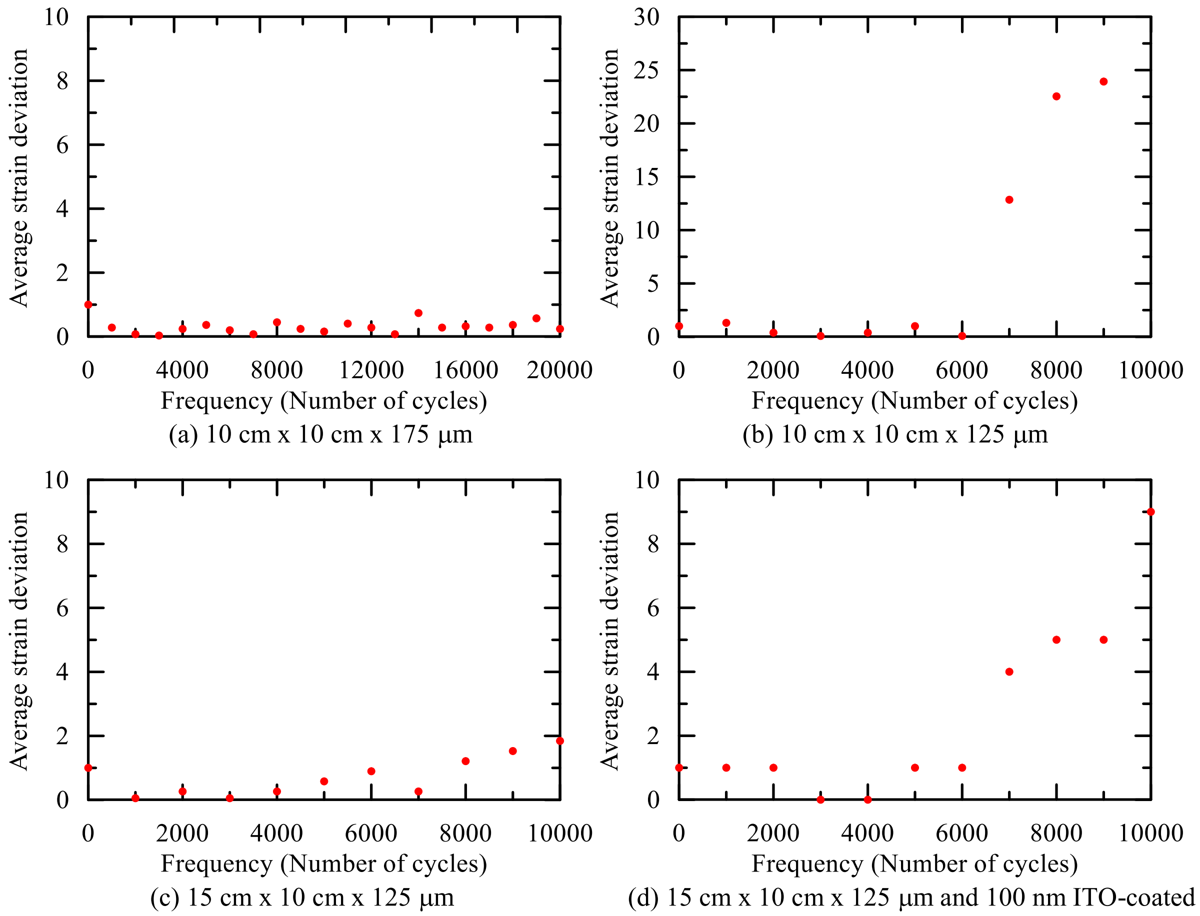


Fig. 4 Dynamic experimental results for PET substrate with dimensions

V. Conclusion

In this study, an experimental method has been proposed for investigating twisting behavior of soft substrates by surface strain measurement. Comparisons among the relationship between surface strain and twisting angle have been made with different dimensions and screen ratios. In this experiment, the surface strains of PET substrates and ITO-coated PET substrates are measured by using optical fiber grating sensing system. It shows that larger strain can be produced with larger torsional angle. Thicker PET substrates suffer larger strains under the same torsional angles. In addition, the average strain deviation is defined to estimate the permanent deformation of PET substrates under dynamic fatigue test with the fixed twisting angle. Experimental results show that the PET substrate with larger screen ratios shows higher stability and the ITO-coated PET substrate shows obvious critical cycles to determine permanent deformation under the same screen ratio. These results serve as the guideline to predict the twisting response of soft substrates and are useful in designing flexible electronics.

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