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Finite element analysis of stress distribution in soft sensors under torsional loading

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Abstract—The wearable and flexible sensors are enabling advances in next-generation technologies such as soft robotics, mobile healthcare, internet of things etc. In consequence, novel materials and manufacturing methods have received most of the attention so far. However, with the growing use of these technologies in real applications, other important areas such as mechanical reliability under repeated mechanical deformations also require greater consideration. A few studies covering this aspect have mainly focused on mechanical stress under simple bending conditions and ignored stress evolution under twisting (torsional) movements. The present work studies the influence of different parameters such as carrier substrate dimensions and its material and twisting angles on the stress distribution during torsional movements using finite element method. Following this, highly stretchable strain sensors are fabricated using nanocomposite of carbon nanotubes and Ecoflex™ and tested under various twisting angles. The soft strain sensor possesses excellent repeatable and robust torsional strain detection properties with >100% change in resistance at ±90° of twisting and has shown potential for wearable and robotics applications.

Keywords—torsion; stress distribution; finite element analysis; strain sensors; flexible electronics

I. INTRODUCTION

Reliable and robust soft sensors in flexible and stretchable form factors are of significant interest in application such as robotics [1-3], the internet of things [4-6], healthcare [7-9], electronic skin (e-skin) [10-16], etc. These sensors are critical in these applications for accurate feedback based on reliable measurements of various stimuli of interest such as pressure, strain etc. During practical applications these sensors operate under intermittent or cyclic mechanical deformations such as bending, stretching, twisting and a combination of these. The sensor response changes with induced stresses during these mechanical movements, and often device failure occurs after repeated stress cycles [17-19]. Therefore, greater attention is needed to predict the response of flexible systems under various mechanical deformations [19-21]. Whilst few attempts have been made in this regard, most of the previous studies have focused only on the analysis of mechanical stress distribution and its effect on device performance under tensile and compressive bending and stretching conditions [13, 19, 22-26]. Whilst these encouraging works mark a step in the right direction, a very few of them have aimed to understand the stress evolution under twisting (torsional) loading [17, 18, 27].

The effect of bending and stretching on device performance degradation has been thoroughly investigated due to ease in stress/strain relationship evaluation during these motions. For instance, bending radius and percentage change in device dimensions can be used to calculate and analyze the induced stress distribution during these movements [28, 29]. Based on these studies, innovative solutions have been proposed to either mitigate mechanical deformations induced performance degradation or exploit the bending to improve device performance [30]. For example, the encapsulation could address mechanical stress related issues by bringing the sensors/devices on neutral mechanical plane [31]. This could enhance the bendability and device stability under bending conditions. However, in real scenario, attaining neutral plane concept is challenging and insufficient to avoid device failure after repeated stress cycles because of much more complex mechanical deformations, such as twisting.

Motivated by these challenges, we present here the stress evolution during torsional (twisting) motions using Finite Element Analysis (FEA). The influence of different parameters such as carrier substrate thickness, material, length etc. and twisting angles on the stress distribution of a 1cm² sample during torsional movements is studied. The sample is clamped on both sides as shown schematically in Fig. 1. Further, we have fabricated a robust soft strain sensor using nanocomposite of carbon nanotubes and Ecoflex™. The sensor is capable of precisely detecting the wide twisting angles.

This paper is organized as follows: Section II describes the theoretical arrangements to study the evolution of stress distribution during torsional loading and fabrication details of the strain sensor. The outcome of various FEA studies and strain sensor change in resistance with twisting is presented in the section III. Finally, key outcomes are summarized in Section IV.

II. EXPERIMENTAL SECTION

A. Finite element analysis of torsional loading

In practical scenarios, a sensor subjected to torsional loads is attached or fabricated on a carrier substrate. Additionally, to evaluate device robustness, the carrier substrate is clamped in the testing machinery. Therefore, for this study we opted to examine the stress distribution on such carrier substrates to gain an understanding on how it varies with different loading conditions and how it could transfer onto the attached device. The FEA simulations were conducted using COMSOL

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Multiphysics and a linear elastic model of the carrier substrate was assumed. Mimicking a commercial twisting test rig, one side of the substrate was assumed to be fixed while the other end was rotated at different angles (0-90° in steps of 15°). Initially a polyimide (Pi) film was used as a carrier and the stress distribution was evaluated for different film thicknesses ranging from 25-125 µm. Additionally, the length and width of the carrier substrate were varied in separate studies. These are shown in Fig. 1a. Lastly, other carrier materials often used for soft sensors were simulated, specifically Polydimethylsiloxane (PDMS) and Polytetrafluoroethylene (PTFE). For all the above simulations, the stress distribution was evaluated for a 1cm² sample and at the center of the carrier’s top surface corresponding to the position a similarly sized device would have been fabricated or attached.

B. Materials and methods for stretchable soft strain sensors

The stretchable strain sensors were fabricated using micromolding-in-capillary process. The details for the process are described elsewhere [32]. The resistive sensing channel is a nanocomposite of multiwalled carbon nanotubes (MWCNTs) and Ecoflex polymer. The MWCNTs were purchased from Cheap Tubes Inc (purity of >95 wt.%) with 8–15 nm outer diameter and length of 10-50 µm. The Ecoflex was purchased from Smooth-On company. The torsional loading was applied using commercial system (Yuasa System DMLHP-TW). Under loading, the electrical resistance was monitored using semiconductor parameter analyzer (B1500A, Agilent).

III. RESULTS AND DISCUSSIONS

A. Finite element analysis of torsional strain

Fig. 2 illustrates the results obtained from FEA simulations of torsional loading. As seen in Fig. 2a, the stress (von Mises) distribution follows a radial pattern with maximum stress observed at the center of the 1cm² region. The increase of the twisting angle resulted in a linear increase in the maximum stress throughout these simulations. Increasing the carrier thickness, also resulted in higher stress values, as seen in Fig. 2b. When varying the carrier width, a smaller change was observed in the maximum stress values, with...
larger stresses developing on wider substrates (Fig. 2c). For a substrate with a width of 10mm, where the assumed device region extends up to the edges of the carrier, the stress distribution changes with the maximum stress observed close to the edges (Fig. 2c inset). Increasing the carrier length reduces the developed stress as seen in Fig. 2e. This is expected since the region of interest is further away from the actuated edge, and it is subjected to a lower twisting angle. Significantly, for a 10mm long carrier where the region of interest extends on the edges of the substrate, the maximum stress is observed at its corners (Fig. 2d). The maximum stress at the corners is significantly higher than the stress observed at the center of the 1cm² region (Fig. 2e). When considering different carrier materials, the stress developed on PTFE is around 1 order of magnitude lower than PI, while for PDMS the stress is more than 3 orders lower (Fig. 2f). The results obtained from these simulations suggest that the carrier material as well as its thickness can impact the amount of stress that a device will experience when under torsional loading. When considering tortional reliability experiments, the placement of a device on the test rig can affect the resulting loading conditions and therefore it should be considered when evaluating such experimental results. In the future work, effect of active device materials such as for silicon, PI etc. with varying thickness will be studied.

B. Fabrication and characterisation of stretchable strain sensors

Fig. 3a schematically shows the fabrication process for soft strain sensors. The process details are reported elsewhere [32]. Briefly, as the first step, standard molding technique was used to generate grooves in Ecoflex (Fig. 3a (i)). For this, standard PI tape was stick to a glass slide and Ecoflex was poured onto the PI/glass slide. Then, Ecoflex was carefully removed and placed upside down onto a glass slide. Next, MWCNTs material suspension was drop-cast at the Ecoflex grooves area. This step was repeated several times to form a continuous MWCNT network (Fig. 3a (ii)). In the third step, Cu wires were attached using silver epoxy paste. Finally, another layer of Ecoflex was poured into the MWCNT connected network and crosslinked with the bottom layer of Ecoflex (realized in step 1). The top Ecoflex layer fully and firmly encapsulates the MWCNTs, and thus improves the robustness of the device.

Next, the fabricated sensor was tested for strain sensing. The previous work has shown the excellent strain sensing characteristics of the sensor under uniaxial stretching and bending. In this work, the MWCNT/Ecoflex sensor was subjected to torsional strains, and its real-time electrical response was recorded under a voltage of 1V. To examine the torsional strain sensing performance, ΔT/r₀ (ΔT = r₁-r₀ where, r₁ is the final resistance after twisting and r₀ is the initial resistance) multiple cycles with a stepwise increase in twisting degrees (±30° to ±90°) was obtained (Fig. 3b). The sensor showed a large working window which confirms the robustness of the device. When the sensor was twisted to ±30°, there was a maximum ~25% relative change in resistance. Its response increases with the higher twisting angles (higher torsional strain), reaching maximum relative change in resistance of >100% at ±90°. Based on its high sensitivity to torsional strains, the fabricated soft sensor has potential applications in wearable electronics.

IV. Conclusions

In summary, we have studied the effect of different parameters including carrier substrate dimensions and its material and twisting angles on maximum stress experienced by devices during torsional loading. It was observed that the maximum stress increases with the decrease of carrier length as well as increase of width and thickness (although the effect of width was not significant). With the increase in twisting angles, the maximum stress was also found to be increasing. Further, the softer carrier substrates such as PDMS showed more than 3 order lower stress generation as compared to PI films. Finally, fabricated soft strain sensors showed robust sensing performance under wide range of twisting angles. The present study lays the foundation for understanding the evolution of stress distribution under torsional loading and, likewise appropriate solution could be implemented in future to avoid performance degradation during such loadings.