Optimization of Bilayer Actuator Based on Carbon Black/Polymer Composites

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Abstract. In the last few years, actuators based on polymer composite have been created for incredible potential applications in the zone of artificial muscle, micro-robots, relays, and energy harvesting. Polymer composites show the more massive deflection or bending due to the electrothermal and photothermal efforts. Subsequently, these have excellent orientation on the effect because of material properties and structure. In this study, theoretical modeling is employed to understand and analyze the actuator performance by incorporating carbon black (CB) into the polymer material. Polydimethylsiloxane (PDMS) acts as a polymer matrix with bilayer geometry. The displacement of bilayer polymer composite is identified by the length and thickness of two layers, the distinction of coefficients of thermal expansion (CTE) between bilayer and temperature change are inspected. Theoretical outcome demonstrates that the displacement is enormously affected by the thickness proportion of bilayer actuator. In this manner, it is optimized by upgrading thickness proportion and distinct parameters of the bilayer actuator. Thus, this investigation will give a hypothetical reference to the realistic design and realization of the CB /PDMS composite based on a thermal input.

1. Introduction
There is growing interest in the design of the actuator system by mimicking nature to yield lifelike motion in response to external stimuli, such as heat, electrical, light, and moisture [1,2]. In recent years, researchers have been exploring materials, which can provide large deformations to different stimuli. Piezoelectric and magnetostrictive materials deliver smaller deflections and consume more power. Shape memory materials are able to produce more considerable deformation but have relatively longer response time [3-5].

Presently many researchers have been interested in polymer composite kind of actuator study. In 2008, Hai et al. have developed a computational model of single-wall carbon nanotube polymer composite for thermal conductivity study [6]. In 2014, Ying et al. have designed and fabricated graphene and polymer composite bimorph actuator has a large deflection under low voltage (1.2 cm-1 at 10 V for 3s) [7]. Thus, comparing with conventional material, polymer materials exhibit high performance, lightweight, fast response, and ease of fabrication. In this way, for the actuator development, polymer composite based materials are widely explored in recent years [8-10]. Polymer-based composite materials possess good electrical, thermal and mechanical properties [11, 12]. Carbon black is introduced into polymer base material to formulate composite material; CB material will enhance the features and performance of the base material [13]. Thus, carbon black placed polymer
composite is used in the micro gripper, micro-robots, micro heater, energy harvesting, sensors, and actuator so on. The composites can transfer different stimulus input into heat and uniformly distributed on to polymer composite. Thus, the thermal properties of carbon black filled polymer composite material will vary and diverted into deflection [14].

The main principle of a thermally induced actuator is adopting two layers of material, which has a different coefficient of thermal expansion between the two materials and forming a bilayer geometry. Hence due to a difference of CTE, the internal stress of the bilayers makes the actuator bends away from the larger CTE. Thus, there are few reports on the numerical analysis of thermally induced deflection based on carbon black and polymer composite. In this paper, a hypothetical examination of bilayer actuator utilizing PDMS and CB-PDMS composite is done. Relationship of a certain important parameter such as geometry, CTE, temperature change with respect to the displacement of bilayer composite actuator is studied. This optimization work will be further extended for appropriate design and fabrication of CB/polymer composite based thermal actuator.

2. Material and Geometry

The geometry of the bilayer strip consists of pristine and composite materials actuator is appeared in figure 1. The material introduced for the analysis of thermal actuator is carbon black and polydimethylsiloxane. PDMS is an organic silicone polymer compound, which is frequently called silicone elastic. It is also known as optical transparency elastomer cured at room temperature silicon rubber. At last cured PDMS has exceptional thermal and mechanical properties [15].

![Figure 1. The geometry of a bilayer actuator.](image)

Thus, the polymer composite material is a double layer structure. One layer is composite of CB and PDMS material, is also named as CB + layer, since, the content of carbon black is more and in other layer named as pristine PDMS layer. Three-dimensional size of the bilayer polymer actuator is included here is 20mm x 5mm x 0.50mm (length x width x thickness). The properties of PDMS and CB+ are shown in Table 1. The Young's modulus, CTE of the polymer composite parameters obtained according to an inverse law by adopting the equation 1 and equation 2.

\[
E_c = \frac{1}{\frac{v_f}{E_f} + \frac{v_m}{E_m}}  \tag{1}
\]

\[
\alpha_c = \frac{1}{\frac{\alpha_f}{\alpha_m} + \frac{v_m}{\alpha_m}}  \tag{2}
\]
Table 1. The material parameter used for analysis.

| Material              | Young's Modulus (E) [MPa] | Density (ρ) [kg/m$^3$] | Poison's ratio (ν) | The coefficient of thermal expansion (α) [1/°C] |
|-----------------------|---------------------------|-------------------------|--------------------|----------------------------------|
| Pristine PDMS         | 0.85                      | 1030                    | 0.45               | $3.10 \times 10^{-4}$            |
| CB/PDMS composite     | 1.57                      | 1054                    | 0.43               | $1.16 \times 10^{-4}$            |

Where, m, f and c represented as matrix, filler, and composite of the material. $E_c$ and $\alpha_c$ speak to Young's modulus and CTE of the CB+ composite layer, $E_f$ and $\alpha_f$ are a reference as Young's modulus and CTE of the carbon black filler material. Furthermore, $E_m$ and $\alpha_m$ are Young's modulus and CTE of the pristine PDMS material. Communicated $\nu_f$, $\nu_m$ as the volume fraction of carbon black material and PDMS material. The estimation of the filler and matrix content is figured to 0.05% and 0.95% individually.

When heating of the bilayer composite actuator, because of a distinction of CTE, the deformation is far from the source, due to pristine PDMS layer has a bigger CTE than the CB+ layer. The solid holding of the two layers brings about the entire actuator creating internal stress and bending to towards the CB+ layer. The boundaries are assumed that one of the ends is settled and another end has free displacement. While stop heating, bilayer will cool off, and the actuator comes back to the original position.

3. Theoretical Modeling
The schematic illustration of the bilayer actuator bending is as appeared in figure 2. In the theoretical examination, some of the assumptions are proposed for bilayer deformation. An assumption is made like (i) There is a uniform heat conveyance inside the actuator and disregarding the heat misfortune (ii) The CTE of material does not change with temperature (iii) The bilayer actuator has a direct appropriation of stress, keeping away from the boundary impacts of the actuator. The displacement of the bilayer actuator is affected by CTE, Young's modulus and temperature change of the bilayer. The horizontal displacement ($\delta$) of the free end of the bilayer cantilever can be expressed with the following relationship.

$$\delta = r - r \cos(\theta)$$  \hspace{1cm} (3)

Where $r$ and $\theta$ are the radius of the curvature and deflected angle appears in the above figure. Whereas, $\theta=L/r$, $L$ is the length of the actuator. The radius of the curvature ($r$) of the bilayer actuator can be communicated as [16].

![Figure 2. Schematic diagram of a bilayer actuator.](image-url)
In case one, the proportion of the thickness is considered for examination, where the thickness of CB+ layer is set as a fixed value and other layer PDMS is considered as a variable. In this study, the thickness variation of the bilayer actuator impacts the high deformation. Subsequently, the factor's is represented as the thickness proportion of the two layers, given by \( m = \frac{t_1}{t_2} \); where \( t_2 \) is approximately fixed to 20 \( \mu \)m and after that \( t_1 = m \times t_2 \) obtained by changing other layer thickness. Alternate parameters utilized for estimation appeared in Table 1. With fixed temperature is substituted in equation 4 to get the curvature of the bilayer actuator.

The examination result appeared in figure 3. The free end of the bilayer actuator displacement is quick increments with the expansion in thickness proportion. It achieves the highest estimation of approximate 11.5 mm at the thickness proportion around 10. Afterward, the displacement slowly decreases with increases in thickness ratio.

Along these lines, the proportion of the thickness is plying the vital part in design and optimization. Since, by considering the thickness of the perfect PDMS layer is thin, for example, near zero, at that point the proportion of thickness winds up zero. Then, the actuator bilayer became a single layer structure of the CB+ layer. Subsequently, there is no distinction between the thermal expansion of the layer. Accordingly, the displacement tends to be invalid after heat input. For another situation, if the thickness of the pure PDMS layer is thick and actuator progressed toward becoming bilayer structure, which has a sizeable substantial contrast in thermal expansion, still the displacement tending to be invalid also. Since the internal stress is exceptionally hard to make such thick actuator deflect after heat input. In a streamlined word, the deflection tends to zero, while the thickness proportion has a tendency to be zero and greatest respectively. Thus, there must be one optimum thickness ratio, where the displacement is highest. In this theory, the assumptions were made for investigation is affirmed that to achieve more noteworthy deflection for sensible application. Hence, need to select an optimum thickness ratio of the bilayer composition.

\[
\frac{1}{r} = \frac{6W_1W_2E_1E_2t_1t_2(t_1 + t_2)}{(W_1E_1t_1^2)^2 + (W_2E_2t_2^2)^2 + 2(W_1W_2E_1E_2t_1t_2)(2t_1^2 + 3t_1t_2 + 2t_2^2) \Delta T} \tag{4}
\]

Where, \( W, t, E, \) and \( \alpha \) are the width, thickness, Young’s modulus, and CTE of bilayer actuator of pristine PDMS (with subscription 1) layer and CB+ (with subscription 2) layer respectively, and \( \Delta T \) is the temperature rise from the room temperature, where \( \Delta \alpha \) is given by the difference in coefficient of thermal expansion (\( \alpha_1 - \alpha_2 \)) of respective material. It is observed from equation 3 and equation 4 of the free end displacement of bilayer actuator, Is mainly depends on length, Young's modulus, thickness, and CTE of the layers. Hence, the optimization of the bilayer actuator decided by many factors. In that, some of the more influencing parameters explored such as ratios of the thickness, length of the actuator, difference in CTE and temperature change.

### 4. Results and Discussion

In case one, the proportion of the thickness is considered for examination, where the thickness of CB+ layer is thin, for example, near zero, at that point the proportion of thickness winds up zero. Then, the actuator bilayer became a single layer structure of the CB+ layer. Subsequently, there is no distinction between the thermal expansion of the layer. Accordingly, the displacement tends to be invalid after heat input. For another situation, if the thickness of the pure PDMS layer is thick and actuator progressed toward becoming bilayer structure, which has a sizeable substantial contrast in thermal expansion, still the displacement tending to be invalid also. Since the internal stress is exceptionally hard to make such thick actuator deflect after heat input. In a streamlined word, the deflection tends to zero, while the thickness proportion has a tendency to be zero and greatest respectively. Thus, there must be one optimum thickness ratio, where the displacement is highest. In this theory, the assumptions were made for investigation is affirmed that to achieve more noteworthy deflection for sensible application. Hence, need to select an optimum thickness ratio of the bilayer composition.
In case two, both the thickness of the bilayer fluctuates. The diversion of the bilayer observed by varying both the thickness of CB+ and pure PDMS layer by fixed input temperature. The analytical outcomes appear in figure 4 and figure 5.

![Figure 5](image)

**Figure 5.** Demonstrates the three-dimensional results of thickness dependance displacement

The three-dimensional results demonstrate that, the actuator of the displacement (D) reliance on the thickness of the bilayer. The contour map depicts that area of the thickness proportion around 33 to 35, where the deformation is moderately high. Keeping in mind the end goal to get more prominent displacement, the thickness of the layers ought not to be too large or too small. From this investigation recommends that pure PDMS layer range is 1-1.5 mm and CB+ layer around 43-46 µm.

In case third, actuator deflection is likewise impacted by the length of the beam. The main key parameter for micro-actuation is the ratio of deflection to length (δ/L). This proportion enables the actuator to bend more with the fixed thickness. As in figure 6 (a) predict the analytical result of the deflection to length proportion relies upon thickness proportion and the variation of effect illustrate as same as a figure. 3. Also, the free end displacement of the actuator is expanding with the expansion in the length of the bilayer appeared in figure 6 (b).

![Figure 6](image)

**Figure 6.** Displacement of the actuator due to (a) Ratio of the displacement to length (b) Change in length.

In additionally investigated the some more prevailing parameter, for example, thermal expansion and temperature change with respect to the displacement of the bilayer actuator. The CTE of the two material decided for estimation. By expecting CTE of the two-layer difference to vary from zero to 10x10^-5/°C. As per the theory, expository outcome gets that bigger the distinction of CTE could be prompt higher deflection is appeared in figure 7(a). At long last, a difference in temperature is additionally outlining the real part in bilayer actuator. Subsequently, figure 7(b) demonstrates the
straight connection with a displacement of the actuator concerning the change in temperature increment. In this way, a thermal impact additionally affects the free end displacement of the bilayer actuator.

![Figure 7. Actuation influence by (a) Difference in coefficient of thermal expansion (CTE) (b) Change in temperature.](image)

5. Conclusion
In outline, the analytical results of bilayer actuator performance based on carbon black (CB) and PDMS composite is implemented effectively. The numerical outcome demonstrates that each layer thickness has a critical impact on the actuator deformation. Subsequently, the thickness of pristine PDMS and CB+ layer ought to be neither too substantial, nor too little. Likewise, bigger CTE difference and temperature change of the bilayer will predict more noteworthy deflection of the actuator. It found that deflection of bilayer actuator not just relies upon thickness likewise different parameters, for example, length, CTE, and temperature of the polymer composite material. This investigation is a reference for the design and fabrication of CB-polymer composite and furthermore a realization of experimental work because of thermal impact.

6. Reference
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