Design of a Passive Thermal Switch with Coupled Bi-Material Triangle Structures

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***Abstract*—Current reported thermal switches use a positive coefficient of thermal expansion (CTE) values with the use of uni and bi-material structures to achieve conduction and insulation states. By contrast, here, we design a multi-material structure that incorporates tailorable positive and extreme negative CTE values to achieve conduction and insulation states. The tailorable value corresponds to a wide range of positive and negative values of CTE from the multi-material structure. By being able to behave as a conductor (ON) and insulator (OFF) at two distinct temperatures, the thermal switch is beneficial in a variety of thermal management applications, including optimized thermal insulation and self-cooling to prevent overheating in electronics and batteries. To achieve this, the thermal switch needs to realize a multi-functional structure having both sizable thermal expansion and high thermal conductivity. Analytical models and simulations are constructed to determine the thermal deformation and heat transport of the multi-material thermal switch.**

Analytical expressions for the CTE are established and simulated from the combinations of positive and negative CTEs pairs. Moreover, finite element-based simulations are made to determine thermal expansion and thermal conductivity. Using a two-step design approach, we first focus on the selection of the materials and then structural modification of the mesostructures to provide a robust method for the design of a passive thermal switch. To simultaneously obtain specific thermal switch states and thermal conductivity, design parameters should be selected with the consideration of the material thermal properties and thermal structural modification. The metastructure design has the potential as a passive thermal switch allowing for a large thermal expansion and an extremely low thermal resistance. With a systematic approach, this work demonstrates that multi-material metastructure can be potentially used as a tool of thermal transport.

***Index Terms*— Metastructure, Negative Thermal Expansion, Architected Materials, Heat Transfer, Thermal Management**

I. INTRODUCTION

The thermal switch is a device that achieves thermal control with two distinct roles - thermal conduction (ON) and thermal conduction (OFF). The switching mechanics between roles rely heavily upon an active and passive thermal switch. An active thermal switch relies on electricity and other external devices to control heat flow. A passive thermal switch relies only on external conditions to smartly adapt to control heat flow. Unlike an active thermal switch, a passive thermal switch has no energy consumption and requires less maintenance to achieve a thermal control system. As a result, the application of a passive switch is generally preferred to an active switch to attain energy efficiency and low cost of production.

For passive thermal switches, bimetallic actuation [1], unidirectional micro-expansion [2,3], bidirectional micro-expansion [4], phase transition [5], shape memory effect of material [6], and magnetocaloric technology [7,8] have been applied to achieve thermal control. To transfer heat from the hot to the cold source, a contact mechanism is used for the adaptation mechanism of the devices, such as how the micro-expansion device controls the ON/OFF states by thermal expansion. In this system, the thermal switch unit on the hot source expands with the increase in temperature creating contact with the cold source. As heat transfers from the hot to cold sides, the thermal conductivity of the constituent materials directly influences the thermal performance. The use metals and alloys with high thermal conductivity is used for an efficient heat transfer during the ON state. However, the metals and alloys have a relatively small CTEs (between 1.2 $\frac{1}{10^{-6}*C}$ and 24 $\frac{1}{10^{-6}*C}$), being difficult to engineering an efficient ON/OFF state. Furthermore, the gap needs to be in order of several microns for the OFF state to minimize heat transfer.

Motivated by these challenges, this work explores the use of mechanical metastructure, known to have positive, zero, or negative values of CTE, to design a passive thermal switch made of metal with a high thermal conductivity that has a large gap at an OFF state. I architect a material model with significant thermal deformation to generate a large gap of the passive thermal switch while having a high conductance for the ON state. The material model is composed of multi-materials and an internal contact mechanism for the design of the passive thermal switch. I achieve this by coupling bi-material triangles with positive and negative CTE that have an incredibly high directional thermal expansion and a contact mechanism with

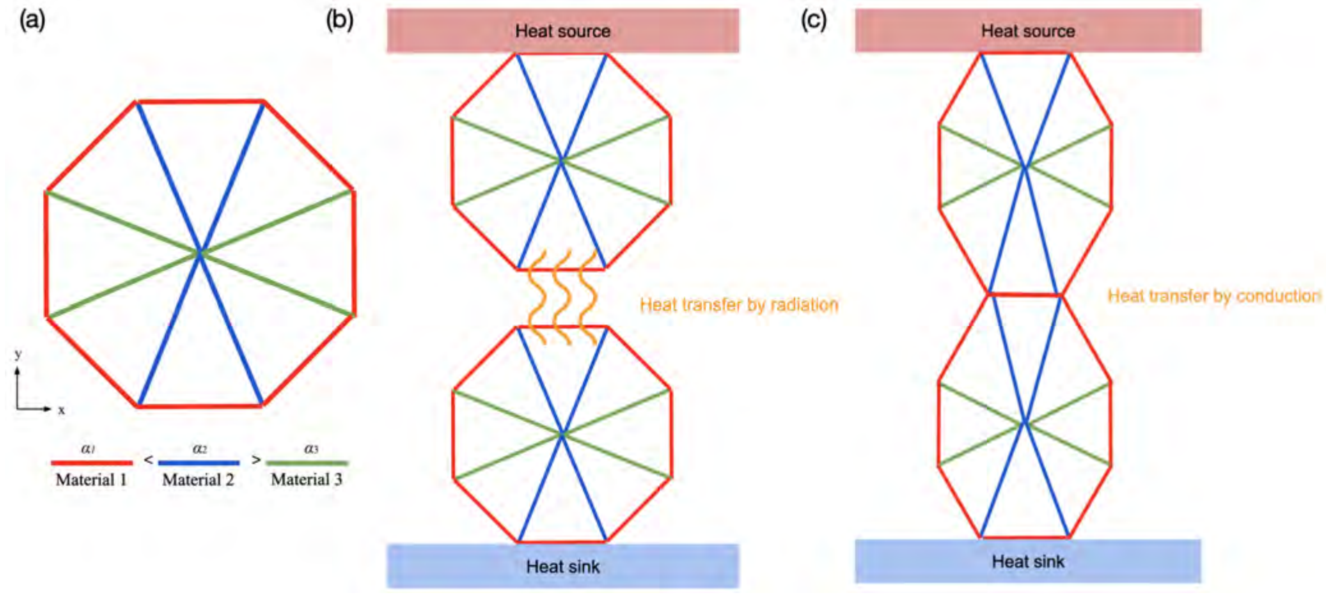

Fig. 1. Coupled bi-material triangle thermal switch (a) schematic of its use for a passive thermal switch; switch OFF (b) switch ON (c)

internal members.

The design goals of the passive thermal switch with coupled bi-material triangles are 1) maximize the heat conduction in the ON state 2) maximize the gap in the OFF state. To do this, it is essential to select a convenient combination of materials and check their thermal and thermomechanical performance. Section 2 describes the principle of the thermal switch of this work. In Section 3, I construct an analytical model on the thermal expansion and thermal resistance of the thermal switch unit. In Section 4, we search candidate materials for the bi-material triangle members from various material groups - metals, ceramics, polymers, and technical ceramics. In Section 5, we create thermal and thermomechnical ANSYS simulations to observe the thermal and thermomechanical performance of the thermal switch. In Section 6, we conclude our work with major findings on the design of a passive thermal switch.

II. BACKGROUND

Recently, mechanical metastructures, structures with a structural capability to break the barriers of physical properties in nature, have been widely used to explore designs of zero or negative values for mechanical parameters such as Poisson's ratio, thermal expansion, stiffness, and dynamic mass density[8-10]. Current works of metastructures separately report the design of tailoring CTE. Most of the available engineering materials always present positive CTEs while more sophisticated designed present negative CTEs such as micro lattice [11], metal lattice[12], bi-material planar lattice[13], and three-dimensional (3D) lattice[14]. By combining the desired thermal direction control and thermomechanical properties of metamaterials, one may provide a solution for the design of a passive thermal switch using both the control of heat flow and thermal deformation. Considering the design simplicity and significant tailorable thermal expansion, I propose a design using the bi-material triangle (triangle lattice) for a passive thermal switch where four bi-material triangles (upper, lower, right, left triangles) are connected and positioned in a fixed heat source and heat sink as illustrated in Figure 1b and c. For the upper and lower triangles, the crossed member CTE is higher than the base CTE. This increases the vertical height of the bi-material triangle. For the right and left triangle, the base member CTE is higher than the crossed member CTE. This decreases the vertical height of the bi-material triangle. When the temperature of the thermal upper switch is low, the thermal switch stays at an OFF state with radiation being the heat transfer. As the temperature starts increasing, the thermal switch changes to an ON state with conduction being the heat transfer. The right and left bi-material triangles contract and create compression forces in the y-direction of the thermal switch. Similarly, upper and lower bi-material triangles expand and create compression forces in the y-direction of the thermal switch. Together, the combination of compression forces results in a flattening of the structure that increases the vertical height of the thermal switch. Note that conduction in the ON state is affected by thermal conductivity, contact surface, and contact pressure between thermal switches A and B.

III. DESIGN OF THE BI-MATERIAL TRIANGLE THERMAL SWITCH

For a heating condition with temperature T, the vertical height change is obtained by the compression forces of the bi-material triangles. With each bi-material triangle influences directly in the magnitude of compression forces, we can derive the total change in vertical height of a singular bi-material triangle:

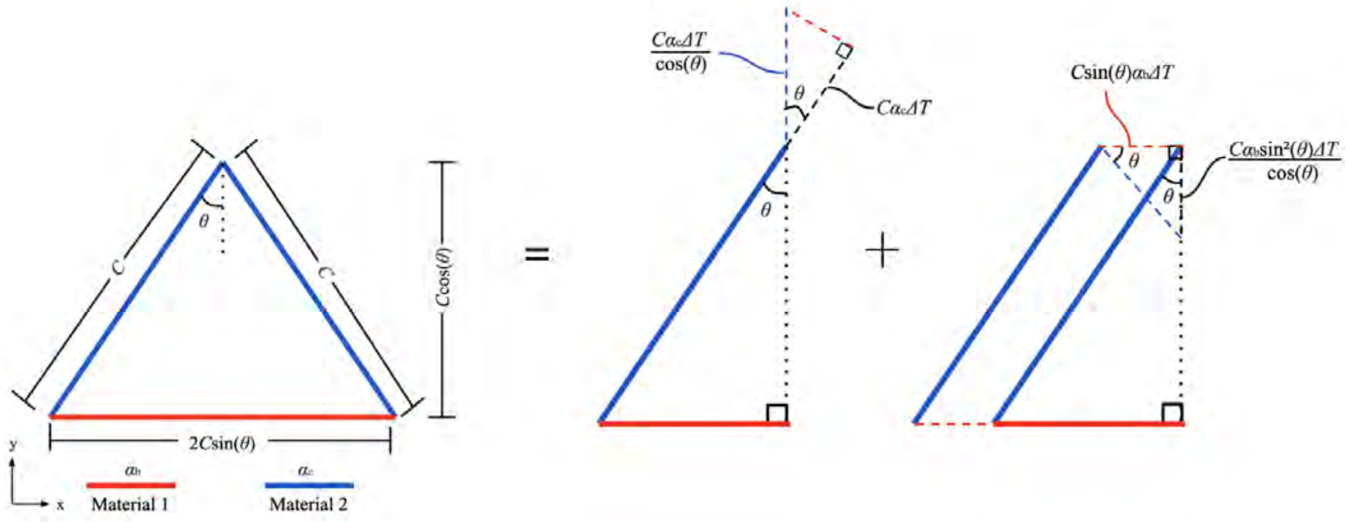

Fig. 2. Derivation of the total height change in the y-direction from the crossed and base components

$$\Delta H = H_f - H_i = \frac{C\alpha_c \Delta T}{cos(\theta)} - \frac{C\alpha_b \Delta T sin^2(\theta)}{cos(\theta)}$$

$$\Delta H = \frac{C\alpha_c \Delta T}{cos(\theta)}\left[1 - \frac{\alpha_b}{\alpha_c} sin^2(\theta)\right] \tag{1}$$

where C is the length of the cross member, α_c is the CTE of the cross member, ΔT is the total change in temperature, θ is half the angle between the crossed members, and α_b is the CTE of the base member. Note that when only the base member expands, the height of the triangle decreases as the crossed member starts to separate from each other. This represents the negative sign in Equation 1. Similarly, when only the crossed member expands, the height of the triangle increases as the crossed member starts to come closer together. This represents the positive sign in Equation 1.

To find the effective coefficient of thermal expansion of the bi-material thermal switch, we use the CTE formula knowing H_f and H_i:

$$\alpha_E = (H_f - H_i)\frac{1}{H_i}\frac{1}{\Delta T}$$

$$\alpha_E = \frac{C\alpha_c \Delta T}{cos(\theta)}\left[1 - \frac{\alpha_b}{\alpha_c} sin^2(\theta)\right]\frac{1}{Ccos(\theta)}\frac{1}{\Delta T}$$

$$\alpha_E = \frac{\alpha_c}{cos^2(\theta)}\left[1 - \frac{\alpha_b}{\alpha_c} sin^2(\theta)\right] \tag{2}$$

As a result, the total deformation of a singular bi-material triangle in the vertical direction is generated by α_c, α_b and θ. In the mesostructure, the upper and lower triangle. Since the bi-material triangles composing the thermal switch are connected, the thermal switch experiences internal stress for the thermal switch to stretch. In order to maximize the stress in the thermal switch, it is beneficial to choose drastically different CTE values for the bi-material triangles. Because the base member of the bi-material triangle is the same structural body, the base member needs to have a medium CTE that falls in between the positive and negative CTE bi-material triangles.

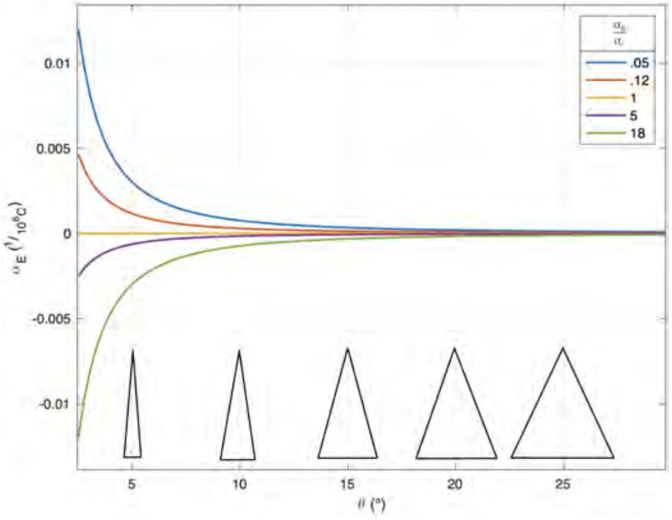

Fig. 3. Adaptable CTE with varying parameters θ

Plotting α_E with a variety of θ with different values of α_c and α_b, we can observe an pattern where α_E increases when θ decreases. This means that the closer the crossed member are in the bi-material triangle, the magnitude of α_E increases. Furthermore, α_E increases when the ratio between α_c and α_b is farther from the value 1. In other words, the bigger the different between α_c and α_b, the bigger α_E.

IV. SELECTION OF MATERIALS

To achieve feasibility in production and low cost of production, materials commonly available for 3D printing and machining (Fig. 4) are considered for the member of the bi-material triangle. For the left and right triangles, the crossed

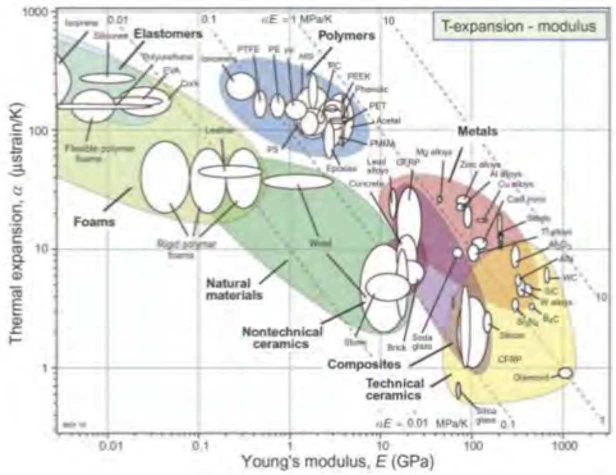

Fig. 4. Material classification with respect to thermal expansion and Young's modulus

members have a low CTE and the base member have a relatively higher CTE. We observe that silica, a technical ceramic, has a low CTE of .55 $\frac{1}{10^{-6}*C}$ and thus composes the crossed member. On the other hand, for the upper and lower triangles, the crossed members have a high CTE and the base member have a relatively low CTE. We observe that Aluminum achieves the highest CTE of the metal with 24 $\frac{1}{10^{-6}*C}$ and thus composes the crossed member. Since the base member is the same body for all bi-material triangles, it needs to achieve a medium CTE between Silica and Aluminum. At the same time, the base's prime job is to transmit heat transfer from the hot source to the cold source. As a result, copper tungsten with a high thermal conductivity 220 $\frac{W}{m*C}$ and medium CTE 6.5 $\frac{1}{10^{-6}*C}$ is the optimum metal to achieve both high thermal conduction and expansion.

V. FINAL DESIGN MODEL AND PERFORMANCE

For the final design model (Fig. 5), the main focus is to maximize the thermal deformation of the thermal switch with the compression forces from the coupled bi-material triangles. To do this, the left and right bi-material triangles have a smaller θ to increase the magnitude of their respective α_E. Furthermore, the upper and lower bi-material triangles have a wider θ to increase the surface contact in the base with the heat source. This allows heat to transfer at a faster rate throughout the thermal switch. Finding a bilateral symmetry in the vertical and horizontal direction, I first design the bottom left section and mirror it to achieve a half-body thermal switch. Then, I rotate the half-body 180 degrees to achieve the coupled bi-material triangle design. To allow freedom of rotation, I use a rotational pin for the contact mechanism of the base and cross members. Ideally, the rotation has a smooth transition to promotes the change of θ and height as temperature increases. Nevertheless, the bi-material triangle has minimum freedom of movement considering the stiffness of metal. As a result, the pin has the secondary purpose of loading stress in the internal body of the thermal switch in the upward vertical direction.

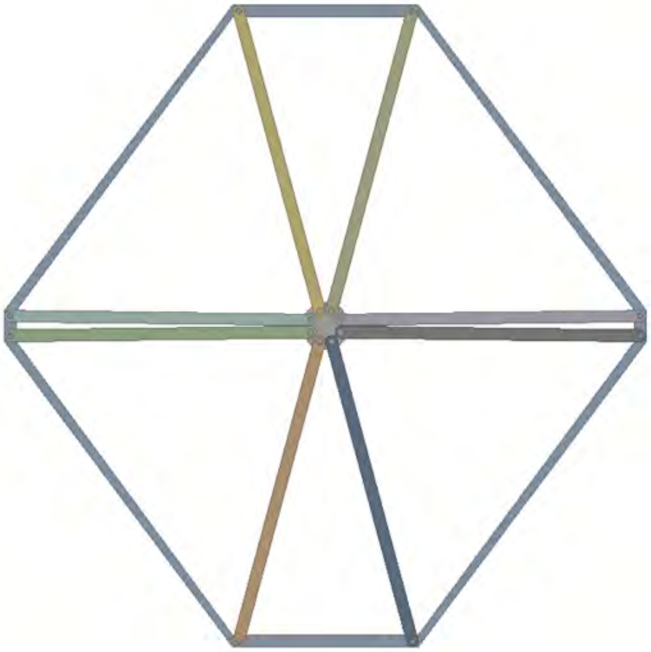

Fig. 5. Modeling of thermal switch with different colors for each separate body

The thermal switch achieves high thermal performance with the upper triangle achieving the same temperature as the heat source with a mere 1 °C difference (Fig. 6). Considering the external body is composed of copper tungsten, the results complement the copper tungsten's high thermal conductivity. Note that upper and lower bi-material triangle crossed members made of Aluminum also achieves a high thermal conductivity in order to give a positive CTE. On the other hand, the right and left bi-material triangles crossed members are made of Silica has a relatively low thermal conductivity and prevents thermal growth in order to give a negative CTE. For the thermomechanical performance, the thermal switch achieves a maximum of .00010936 m total deformation. The side of the upper triangle makes physical contact with the cold source and the rest of the base buckles in the opposite direction. This is the result of compression forces gathering in the side of the upper triangle, making it bounce back in the opposite direction due to the copper tungsten's high stiffness.

VI. CONCLUSION

I propose the use of coupled bi-material triangles with positive and negative CTE for the design of a passive thermal switch. I construct analytical models of thermal and thermomechanical performance, providing a design guideline of the passive thermal switch. Using analytical models and numerical simulations, we selected aluminum and silica for the composition of the positive and negative CTE bi-material triangle respectively with a copper tungsten backbone. I further refined the geometry of the mesostructure to maximize the thermal deformation to minimize thermal resistance. The significance of the bi-material triangle demonstrates potential in thermal

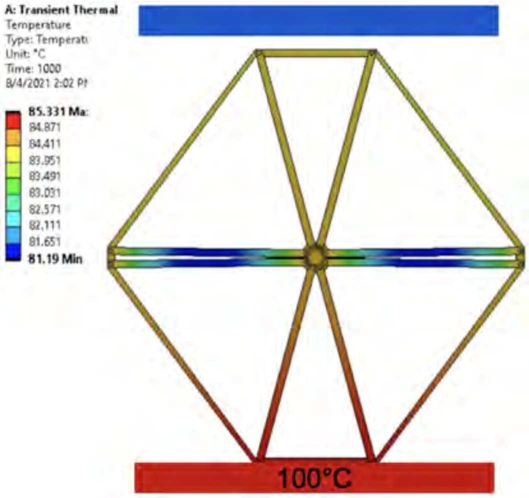

Fig. 6. Transient thermal results with 21 °C as initial temperature and 100 °C as heat source temperature in the lower body component

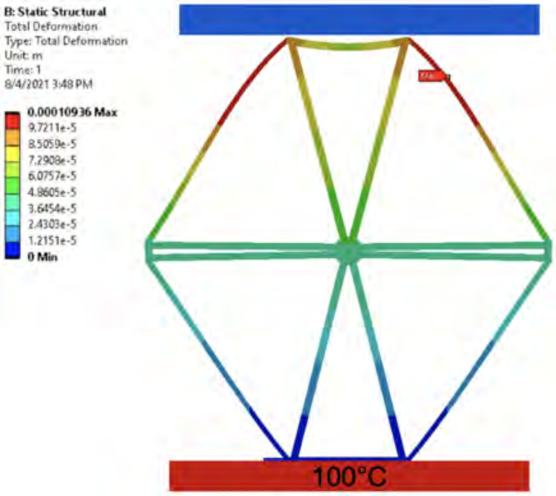

Fig. 7. Total deformation considering thermal expansion and internal mechanical forces

expansion in the several microns with the replacement of the copper tungsten backbone with a more malleable material. This is achieves using only one material for the backbone reducing significant thermal resistance. Considering that most of the thermal expansion accumulates in the sides of the upper triangle, flexible material can promote a higher thermal deformation in the vertical direction. Furthermore, a smoother pin rotation can be helpful to achieve a higher compression force in the internal body of the structure. My work provides new insight into the design of mechanical metamaterials on thermal management. The optimum selection of multi-materials and the geometric modification of mesostructures are essential for the design of passive thermal switches where several confliction design requirements coexist.

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