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Kirigami-based Mechanical Metamaterials

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Metamaterials derive their properties from geometrical shapes rather than physical properties of materials. Mechanical metamaterials are an important class of metamaterials that are becoming an emerging frontier in scientific research and engineering innovation, due to their unprecedented mechanical properties, such as negative acoustic indices, negative Poisson's ratio, negative compressibility, and vanishing shear modulus, arising from the innovative geometrical designs. When in response to different stimuli, metamaterials can be reconfigured beyond their original shape by reversibly changing the size, shape, and symmetry. Reconfigurable metamaterials offer an enhanced flexibility in performance due to their coupling between dynamically changing structural configuration and tunable properties. This field synergistically integrates mechanics, geometry, design, properties, and functionality, which are of tremendous interest in design of flexible electronics, smart windows, actuators, sensors, and photonic/phononic devices.

Structural reconfiguration in mechanical metamaterials has been realized *via* two major strategies: 1) Harnessing buckling instabilities in 2D/3D metamaterials composed of periodic porous or composite structures, where pattern transformation is driven by *compressive* buckling; 2) Origami inspired metamaterials *via* folding. However, both compressive buckling and origami-based metamaterials still fall into the category of compactible metamaterials. The less-stretchability beyond unbuckled state or unfolded origami largely limits their applications in other advanced technologies such as stretchable electronics, where large tensile deformation is often experienced. Thus, design of stretchable metamaterials is highly demanded.

Very recently, the concept of kirigami has attracted growing interest in harnessing cuts for potential applications in pluripotent materials, stretchable and conformable electronics and batteries, solar tracking, and self-assembled 3D meso-structures. In contrast to the compactable origami-based metamaterials, the opening of cuts in kirigami structures enables the generation of a new class of 2D and 3D expandable and reconfigurable kirigami metamaterials.

In this talk, we will discuss our group's recent progress in the 2D and 3D expandable and reconfigurable kirigami metamaterials [1-3] generated by applying the kirigami approach to a thin sheet made of non-active/active materials via line cuts opening and folding. We will first discuss the simple kirigami structure by introducing 1D parallel line cuts to thin sheets [1]. Upon stretching, it leads to the pore opening and tilting feature of cut units. Different from the in-plane rotation, the out-of-plane buckling renders a high stretchability of the structure. However, the tilting direction of cut units is indeterminate, depending on the stretching methods. To address the challenge, we demonstrated two ways, introducing patterned notches and attaching thermal-shrinkable tapes, to the connecting junctions in both sides of kirigami sheets to break the deformation symmetry, thus leading to controllable kirigami structures with programable tilting orientations on demand in both mechanical and stimuli-responsive ways. We further demonstrated kirigami structures with programmable tilting orientation for potential applications as energy-saving building envelopes.

In the second part, we will discuss a more complex hierarchical kirigami metamaterials by introducing hierarchical orthogonal cuts for designing extremely stretchable metamaterials [2-3]. The studied kirigami metamaterial was a thin sheet of materials consisting of hierarchically cut lattice structures fabricated by a laser cutter. Three orthogonal cuts divide a square into 4 connected sub-squares, forming a level 1 structure. A hierarchical structure with self-similarity can be constructed by repeating the same cuts in each sub-level of the square units, leading to a level 2 and higher-level hierarchical structure. Upon stretching, each cut unit rotates around hinges to generate an expandable and stretchable lattice structure even in rigid and non-stretchable materials such as paper. We exploited and characterized the mechanical behavior of hierarchical kirigami metamaterials through both experiments and FEM simulations, including high stretchability, highly non-linear stress-strain curves, and tunable negative Poisson's ratio and acoustic band gaps. We demonstrated that the hierarchical cut concept can be used to design ultra-soft materials with tailorable nonlinear mechanical properties. The potential applications in programmable kirigami machines will be discussed.

References

[1] Tang, Y., Lin, G., Yang, S., Yi, Y.K., Kamien, R. D. and Yin, J., 2017. Programmable kiri-kirigami metamaterials, *Advanced Materials,* 1604262

[2] Tang, Y. and Yin, J., 2017. Design of cut unit geometry in hierarchical kirigami-based auxetic metamaterials for high stretchability and compressibility. *Extreme Mechanics Letters*, 12, pp. 77-85 [3] Tang, Y., Lin, G., Han, L., Qiu, S., Yang, S. and Yin, J., Design of hierarchically cut hinges for highly stretchable and reconfigurable metamaterials with enhanced strength. *Advanced Materials,* 27, pp. 7181-7190