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Parametric Modelling and Optimization of Spinodal Decomposition-Inspired Metamaterials

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Additive manufacturing technology has been rapidly evolving in recent years, leading to a paradigm shift in material design, particularly for metamaterials. In this work, metamaterials with spinodoid topologies are investigated. These topologies are derived from the physics of spinodal decomposition process, which results in a bicontinuous (two-phase) structure. Since spinodal decomposition is deterministic and these topologies are typically non-periodic, they offer a wide design space and can exhibit anisotropic properties that can be tuned with a few parameters. These features make them highly suitable for applications requiring tailored mechanical, thermal, or multi-physical properties.

Unlike traditional metamaterials designed through geometric or topological optimization, spinodoid microstructures can be engineered by tuning the parameters of the Cahn-Hilliard equation, that is the mathematical model that simulates the spinodal decomposition phenomenon. This approach enables the generation of virtually infinite configurations, as the solution to the Cahn-Hilliard equation varies significantly with the physical parameters.

Building on our previous studies, the key parameters of this model have been reduced to just two, enabling a more straightforward material design process. These parameters control the evolution of the diffusional process and the resulting phase field, which is then transformed into a regular and smooth metamaterial sample. As a result, the parameters directly influence both the design and the mechanical response of the metamaterial.
The reduction to only two controllable parameters represents a key advantage: the design process is significantly simplified while maintaining a high degree of versatility. In addition, this feature can be exploited in a simple optimization process aimed at identifying metamaterial configurations with specific multi-physical properties, such as tailored thermo-structural behavior.

This work presents a parametric modeling approach to design metamaterials inspired by spinodal transformations, utilizing only the two dimensionless parameters introduced in prior studies. By systematically varying these parameters, a diverse set of metamaterial samples is generated, and their properties of interest are evaluated. Furthermore, it is demonstrated how the topology of this metamaterial can be optimized to achieve specific performance in terms of anisotropic elastic response, driven only by these two key parameters. This methodology not only enables the exploration of a wide design space but also facilitates the inverse homogenization process, allowing for the tailored optimization of metamaterials to meet specific functional requirements.

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