Entangled particles as engineered architectured materials

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Abstract

Typical noncohesive granular materials based on spherical or other convex geometries have relatively low shear strength and no tensile strength. Individual grains can however be designed with non-convex geometries to generate interlocking, entanglement and tensile strength. Interestingly entangled matter is found in nature (Fire ant rafts, burr seeds), and recent studies on staple-like particles have shown unusual and interesting properties. Entangled matter indeed provides intriguing perspectives in terms of deformation mechanisms, mechanical properties, assembly and disassembly. While some of their attributes and mechanisms share some traits with traditional granular materials, few studies have focused on entanglement and strength and there are large gaps in our understanding of the mechanics of these materials.

We have recently developed a simple "pick-up" test to measure the entanglement in staple-like particles with various leg lengths, crown-leg angles, and backbone thickness. Interestingly some of these parameters have a non-monotonic effect on entanglement, with a clear optimum entanglement for certain combinations of crown-leg angles and leg lengths. This suggests that competing mechanisms are play in the entanglement process, and to capture these effects we developed a "throw-bounce-tangle" model based on a 3D geometrical entanglement criterion between two staples, and a Monte Carlo approach to predict the probabilities of entanglement in a bundle of staples. This relatively simple model is computationally efficient, and it predicts an average density of entanglement which is consistent with the entanglement strength measured experimentally. The model confirms that entanglement is very sensitive to the thickness of the backbone of the staples, even in regimes where that thickness is a small fraction (< 0.04) of the other dimensions. We also demonstrate an interesting use for this model to optimize individual staple-like particles for maximum pairwise entanglement.

Collective entanglement mechanisms are however more complex and they occur over multiple length scales. To study these collective effects, we developed tensile tests on staple-like particles, focusing on the effect of adjusting the angle between the legs and the crown in individual staples. Our experiments, combined with discrete element models, confirm the competing mechanisms between entanglement strength and geometric engagement between particles, giving rise to an optimum crown-leg angle that maximizes strength. We also show that tensile forces are transmitted by a small fraction of the staples, which is organized in only 1-3 force chains. The formation and breakage of these chains is highly dynamic: as force chains break, they are replaced by fresh ones which were previously mechanically invisible.

Entangled matter as "granular metamaterials" offer interesting perspectives in terms of materials design, and a vast design space for individual particles. Since their properties can

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be tuned with the shape of the staple, we interpret these entangled materials are "granular metamaterials" with unusual combination of properties: simultaneous strength and toughness, controlled assembly and disassembly, re-conformability and recyclability.