Unlocking innovation: Multistable mechanical metamaterials' evolution in design, manufacturing and applications

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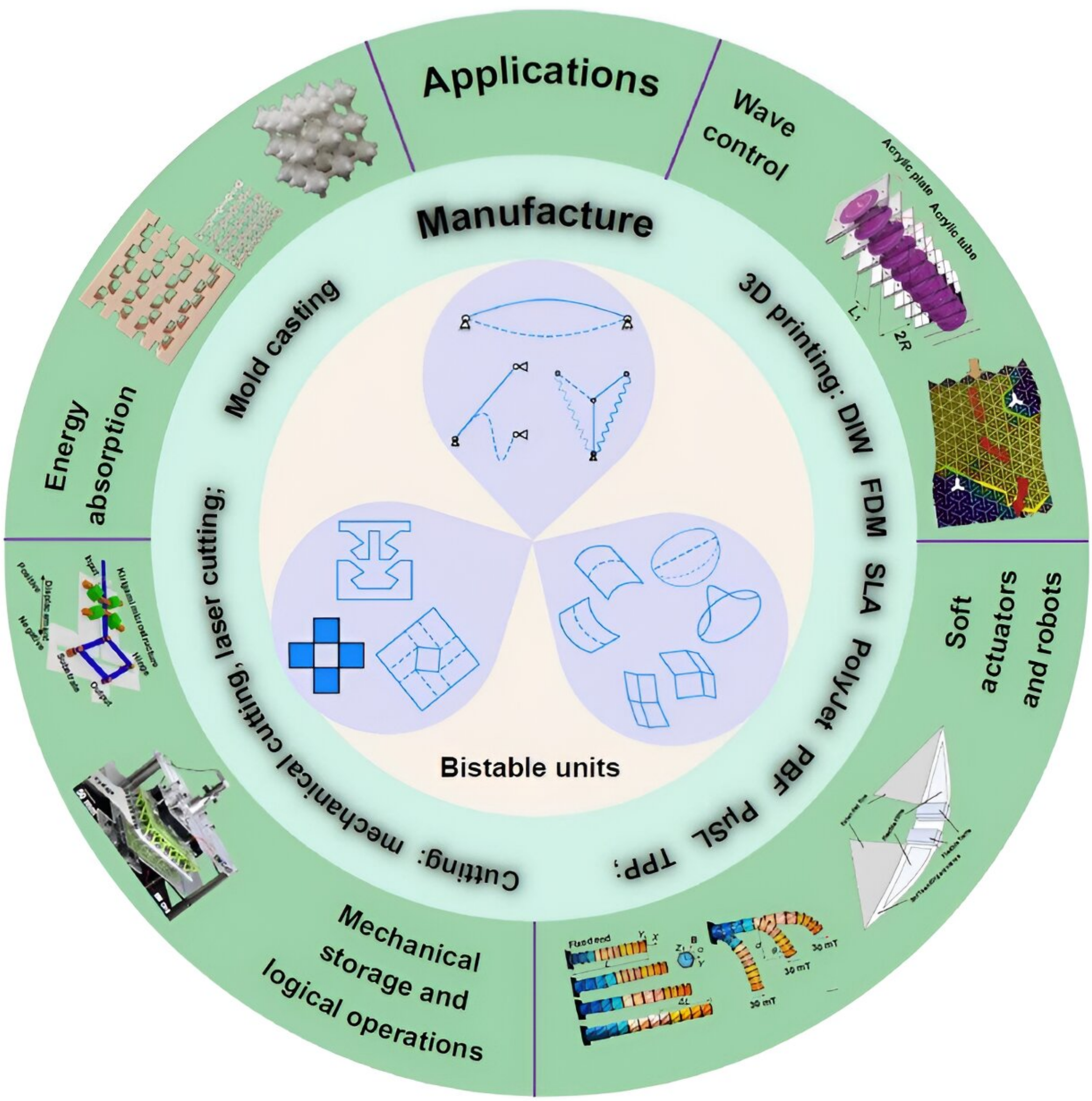

The three innermost leaves contain three basic bistable units. The intermediate ring describes the basic preparation methods of multistable metamaterials: 3D printing (DIW, FDM, SLA, PolyJet, PBF, PμSL, and TPP), cutting (mechanical cutting and laser cutting) and mold casting. The outermost ring describes the potential applications of multistable mechanical metamaterials: energy absorption, soft actuator/robot, mechanical storage/logic operation and wave control. Credit: By Rui Xu, Chuanqing Chen, Jiapeng Sun, Yulong He, Xin Li, Ming-Hui Lu and Yanfeng Chen.

Researchers from Nanjing University reviewed the latest research progress in the design, manufacturing, and application of multistable mechanical metamaterials with the remarkable ability to switch between multiple stable configurations under external loading. The realization of reusability positions these innovative metamaterials for a wide array of engineering applications, including energy absorption, soft actuators/robots, mechanical storage, logical operations, and wave control.

Published in *International Journal of Extreme Manufacturing*, this research begins by summarizing and categorizing common bistable units, thereby establishing a foundation for bistability assessment—an aspect previously underexplored in existing research. The mechanical properties of bistable structures are then scrutinized from an energy perspective.

In the realm of multistable mechanical metamaterial fabrication, the research not only introduces conventional subtractive manufacturing methods, such as cutting, but also spotlights cutting-edge material processing techniques, including 3D/4D printing.

Given the exceptional properties of multistable mechanical metamaterials, their potential for application extends broadly to domains such as energy absorption, soft robotics, and wave control, among others. Finally, the research delves into an analysis of future research directions and the challenges that lie ahead in the field of multistable mechanical metamaterials.

"Multistable mechanical metamaterials are pretty awesome—they can switch between different stable shapes, making devices reusable. Plus, their energy barriers are handy for energy absorption and storage. When they shift from one stable state to another, they release strain energy quickly, making them super-efficient for quick action. And the best part? They don't need a constant energy supply for steady-state deformations. They're also rich in deformability and can do all sorts of cool stuff," said Ming-Hui Lu, a professor of college of Engineering and Applied Sciences at the Nanjing University and the senior author on the study.

"These properties make multistable mechanical metamaterials promising for a wide range of applications in many fields, such as soft actuators/robots, mechanical storage/logic operations, energy absorption, wave control, and so on," Lu added.

"We can find bistable structures all over the place, both in nature and in our everyday stuff. The Venu's flytrap leaves go from 'open' to 'closed' or a hummingbird's beak snapping shut in just a few milliseconds to grab a tasty insect. Even everyday things like switches, bottle caps, pen caps, plastic buckles, cable ties, those bouncing toy balls, tape measures, and hair clips use bistable designs," said Xin Li, a professor of school of Mechanical Engineering at the Nanjing University of Science and Technology.

Li said "We categorize these common bistable structures into three categories, which fills the gap in previous research. They are: beams, trusses, and compliant mechanisms; curved surfaces and thin-shell structures; and other structures such as kirigami and snap-fit structures."

The preparation of multistable mechanical metamaterials is a prerequisite for their engineering applications, and there are numerous fabrication methods regarding those metamaterials.

Then, Li explained that "Besides the traditional subtractive manufacturing like cutting (with machines or lasers) and mold casting, there's this newfangled thing called 3D/4D printing that's been taking off like crazy. This tech's come a long way in the last few years and is making it super easy to create those intricate multistable mechanical metamaterials. Especially when it comes to printing them with pinpoint accuracy or making them in different sizes, 3D/4D printing gets some serious perks."

For the future development of multistable mechanical metamaterials, Lu said, "AI's the hot topic right now, especially for designing, modeling, and optimizing things. So, if we mix good traditional design and simulation methods with AI, we can make designing these metamaterials a piece of cake. It's all about simplifying the process, focusing on key parameters, and boosting design efficiency."

"I'm pretty stoked about the future of multistable mechanical metamaterials because there are some cool new manufacturing technologies. Take micro-nano 3D printing, for instance. Stuff like PμSL and TPP has been a game-changer, letting us create these tiny multistable structures."

"Plus, when we use top-notch materials and advanced 3D printing and post-processing tech, we're not just making them look good, we're making them tough too—strength and all that jazz. It opens up doors to use these multistable mechanical metamaterials in all sorts of fields like aerospace, medicine, electronics, and robotics. We can even make these metamaterials using soft-driven materials and 4D printing wizardry. That means we can control them with all sorts of stuff like electricity, light, temperature, pH levels, solvents, moisture, and magnetic fields," Lu commented.

The application of multistable mechanical metamaterials also faces a number of opportunities and challenges. "When it comes to energy absorption, they're not great at absorbing energy compared to the usual materials."

"But there's a fix for that! We can tweak the design, use high-energy-density materials, mix them with the regular energy-absorbers, and even create multi-stage energy-absorbing setups to amp things up. We can make these structures bend and flex on command by tossing in some materials that react to outside signals. That super-fast changing shape makes them perfect for powering soft robots and actuators in a snap."

"These bistable structures can store data as binary states without needing power. That means they can handle some seriously rough environments like high radiation, scorching heat, or intense pressure. When you combine them with mechanical computing, you've got machines that can think and adapt all on their own. And don't be surprised if you see these mechanical brains shrink down to the micro and nano level with the rise of tiny 3D printing tech," Lu said.

In the past decade, scientists have shown great enthusiasm for the research of multistable mechanical metamaterials, and have achieved remarkable results. The team believe that the continuous improvement of multistable mechanical metamaterials theory and manufacturing technology will greatly promote their application in more engineering fields.

More information: Rui Xu et al, The design, manufacture and application of multistable mechanical metamaterials-a state-of-the-art review, *International Journal of Extreme Manufacturing* (2023). DOI: 10.1088/2631-7990/acf96a

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