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Manufacturing Interlocking Structural Components by FDM

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Abstract. Interlocking structure is a commonly used method for connecting two or more incompatible components, offering advantages such as the absence of external connections, increased stability, and the capability for disassembly and reconfiguration. This method has already been applied in the field of 3D printing. Past research has primarily focused on two-dimensional interlocking structures, mainly those with dovetail mortise types, such as puzzle-shaped, star-shaped, trapezoidal, and T-shaped structures. In-depth studies and optimization of their mechanical properties, including tensile strength and load-bearing capacity, have been conducted. However, the two-dimensional interlocking structure cannot meet the needs of all application scenarios due to the inevitable limitations of its own structure. In recent years, research has begun to focus on three-dimensional interlocking structures, and the concept of three-dimensional topological interlocking structures has been proposed. The three-dimensional interlocking structure is more complex compared to the two-dimensional interlocking structure, adding restrictions on vertical movement and resolving some limitations of the two-dimensional interlocking structure. There now exist three-dimensional topological interlocking structure models that possess a certain level of strength and are suitable for manufacturing using Fused Deposition Modeling (FDM), which have been tested and proven effective. This article summarizes the characteristics, advantages, and disadvantages of two-dimensional and three-dimensional interlocking structures, their applications, and potential future development directions.

Keywords: Interlocking, additive manufacturing

1. Introduction

FDM 3D printing is an important method for manufacturing interlocking structures. Compared to traditional manufacturing, 3D printing offers greater freedom in producing complex geometries and customized parts. Traditional manufacturing is unable to produce certain components with high geometric complexity, whereas 3D printing is capable of producing such components. Rossing et al. proposed a method to control the adhesion between silicone and plastic components through mechanical interlocking. This method enhanced the adhesive strength and also improved the design flexibility and customizability [1].

This article lists some commonly used two-dimensional interlocking structures, such as puzzle shapes and star-shaped structures, and summarizes their respective characteristics and advantages.

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Subsequently, this article summarizes the limitations of two-dimensional interlocking structures and the characteristics and advantages of three-dimensional interlocking structures, as well as some existing research findings. In conclusion, this paper summarizes some applications of interlocking structures, as well as potential future directions for development.

2. Two-dimensional interlocking structures

2.1. Design principles

The two-dimensional interlocking structure is an interlocking system primarily based on a dovetail mortise structure, as illustrated in Figure 1, and is a common method for connecting two incompatible materials. This type of structure, found in living organisms in nature, has inspired engineering construction. Two-dimensional interlocking structures come in various forms.

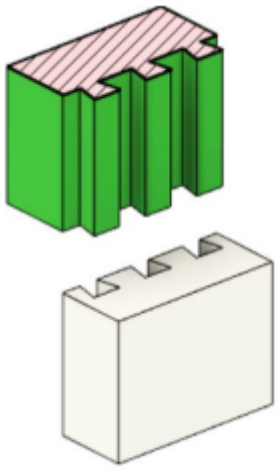

Figure 1. Dovetail mortise interlocking structure [2]

2.2. Puzzle-shaped structure

In Figure 2. In the natural world, structures such as bird beaks, bones, and shells exhibit high strength, toughness, and deformability. Such types of biomaterials can be referred to as sutured materials. The interface of natural suture has complex geometries and concave features that can enhance the overall mechanical properties. Puzzle-shaped sutures also have such a function. Malik et al. conducted a study on the mechanical properties of puzzle-shaped sutures. They primarily focused on the pull-out response of the sutures. Research results indicate that the pull-out resistance of sutures increases with the increase of the interlocking angle and the coefficient of friction. However, when the interlocking angle is large, the sutures are more prone to failure due to breakage. Lubricating the sutures reduces the frictional resistance, which can increase the interlocking angle at which the sutures remain intact. They ultimately concluded that a low friction coefficient and a high interlocking angle are more conducive to maximizing stiffness, strength, and energy absorption [3].

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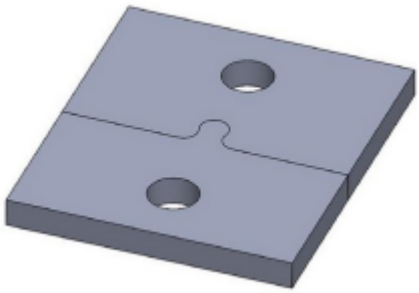

Figure 2. Puzzle-shaped two-dimensional Interlocking structure [3]

2.3. Star-shaped

As shown in Figure 3, a Star-shaped suture is a type of hierarchical geometric structure that possesses superior mechanical properties. The hierarchical structure can increase the tensile strength of the interlocking structure by 57% [4]. Starting with the triangle as the first level, a hierarchical structure is formed using an iterative process. In the first iteration, the two sides of the triangle are divided into three equal parts. According to the Koch rule, the middle segment of each side is replaced with two equal-length line segments that form an angle of 60 degrees, creating a small triangle. This is referred to as the second level. By repeating this process, the Nth-order structure will be generated. Wang et al. studied the design of this hierarchical triangular suture joint. Research findings indicate that increasing the number of levels in a hierarchical structure can enhance the overall strength. However, a three-level structure, while stronger than a two-level structure, exhibits a sudden drop in load after reaching its peak, manifesting as a brittle fracture and losing its ductility [5].

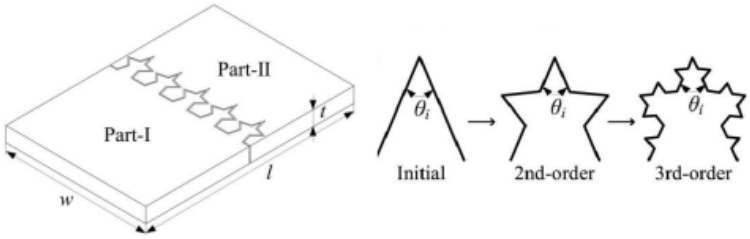

Figure 3. Star-shaped two-dimensional interlocking structure [5]

In addition, the two-dimensional interlocking structure also includes trapezoidal sutures, T-shapes, and other forms. At the trapezoidal suture, the interfacial stress is highest at the flat tip area of the trapezoid, while the tooth stress is highest at the base of the trapezoidal tooth. The triangle suture is less prone to breakage due to the relatively uniform distribution of stress. On the contrary, the trapezoidal suture can form interlocks. Although the stress distribution is relatively concentrated and more prone to breakage, it exhibits greater tensile strength under non-breakage conditions [6]. As for the T-shaped interlocking structure, research by Ribeiro et al. indicates that it possesses a higher fracture strain, which can enhance the mechanical properties of the interface [7].

2.4. Limitations

The most notable limitation of a two-dimensional interlocking structure is that it can only operate within a single plane, restricting the movement of objects along the X and Y axes, while movement

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along the Z axis may still occur, resulting in reduced stability. At the same time, there must be key components in the two-dimensional interlocking system, which are the remaining movable parts after assembly in a specific order. But in a three-dimensional interlocking structure, if the external edges are constrained, there is no need for the key components [8]. In addition to the inherent limitations mentioned above, two-dimensional interlocking structures also tend to experience increased brittleness along with heightened strength, making it difficult to simultaneously achieve both high strength and high toughness.

3. Three-dimensional interlocking structure

A. Dyskin et al. proposed the topological interlocking structure in 2001 [9]. They designed a tetrahedral interlocking assembly and conducted tests on its load-bearing capacity and rigidity. Preliminary test results indicate that interlocked tetrahedral components can maintain structural integrity even when subjected to significant localized loads.

Kuipers T. et al. proposed another type of topological interlock. This structure allows connected parts to maintain interlocking under any degree of continuous deformation and can only be destroyed by discontinuous deformation [2].

3D printing such structures requires continuous and uninterrupted printing on each layer as much as possible, in order to avoid defects such as precision issues arising from intermittent printing. This was achieved through the interlaced topological interlocking lattice (ITIL) designed by Kuipers T. et al. As shown in Figure 4, ITIL consists of horizontal beams arranged in alternating directions along the Z-axis, with beams oriented in different directions connecting to form vertical columns at their intersection. This structure has no isolated sections at each cross-section, making it suitable for FDM printing. Additionally, this structure possesses a certain level of tensile strength and can still maintain a degree of effectiveness even when partially damaged [2].

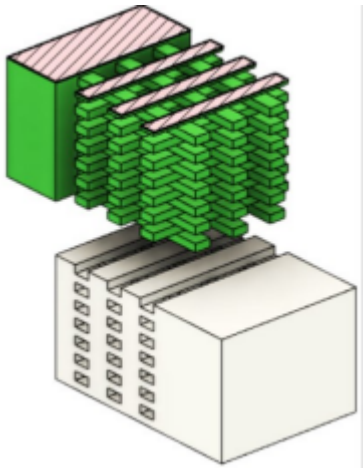

Figure 4. Interlaced Topological Interlocking Lattice (ITIL) [2]

Yao et al. applied interlocking structures to the path planning of 3D printing. They proposed a repeated structure consisting of five layers. This structure enhances the degree of inter-layer connectivity, thereby reducing the anisotropy of the printed components [10].

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4. The application of interlocking structures

The interlocking structure is used to connect two components and serves as an alternative method for bonding parts together when external connectors are not available or desired, replacing the traditional use of adhesives, nails, or hinges. Compared to conventional methods, it allows for disassembly and reconfiguration. In addition to puzzles and other intellectual toys, interlocking structures can also be applied in furniture and architecture. In furniture, interlocking structures can be used for assembling parts, while in architecture, they can reduce the use of nails [11].

In multi-material printing, harder materials can be utilized at designated rigid components, while flexible materials are employed at the joints to connect the rigid materials, thereby interlocking the two through a structured connection [2].

Some interlocking structures provide important insights for cooperative 3D printing (C3DP) with synchronized multiple robots. By using topological interlocking connections between components after partitioned printing, collisions between robots can be avoided, thereby simplifying the issues related to path planning [12].

Interlocking structures can also be utilized for laser cutting. Song et al. proposed a method for connecting planar components cut by laser into a three-dimensional structure through interlocking structures. The base is manufactured using laser cutting, while the shell and connectors are produced using FDM. This method combines the advantages of 3D printing and 2D laser cutting, allowing for the creation of highly freeform shapes while reducing the volume associated with 3D printing. This consequently decreases the costs of high-priced materials and the generally longer printing time, transforming it into a low-cost and time-efficient laser cutting process. As a result, it enables the economical and rapid manufacturing of large three-dimensional objects [13].

5. Existing deficiencies and development trends

The three-dimensional interlocking structure solves some of the limitations of the two-dimensional interlocking structure, but there is still a need for further research. For different printers, factors such as printhead position, spinneret diameter, and temperature are different, which will have a greater impact on the final effect, and the position on the platform will also affect it [2]. Different materials may also have different effects. In the experiment, only the effect of the structure on specific tensile or pressure situations was tested, and further experimentation and optimization were needed for more different conditions, and more variants will be designed.

In future work, the three-dimensional interlocking structure will receive more attention, and may design suitable interlocking structures can be designed for different printing conditions and different materials, or a structure that is less affected by the above factors can adapt to different conditions and is effective under these differences, so that stable production and manufacturing can be proposed. Optimizing the printing path and overall structure to make the interlocking structure less susceptible to discontinuous deformation is also an important concern. In addition, it is possible to design structures that combine 2D and 3D interlocks, combining multiple advantages [2].

6. Conclusion

Interlocking structures have been widely used in many fields and are receiving more and more attention. Most of the past studies have paid attention to two-dimensional interlocking structures, which have unavoidable shortcomings but still have superior mechanical properties and play great value. The advantages of three-dimensional interlocking structures are gradually being discovered,

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and research results have been obtained in recent years. In addition, the interlocking structure is compatible with 3D printing and has been used in a large number of applications. In the future, 3D interlocking structures will receive more and more attention, and interlocking structures that are more suitable for 3D printing may be designed.

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