Additive Manufacturing of Furniture Corner Guards Based on Thermoplastic Polyurethane Filament

Chen Wang,[a,b,*] Jingyao Li,[a,b] Tianyi Wang,[a,b] and Xiaowen Wang [a,b]

Furniture corners are the most vulnerable areas to be damaged by collisions or to cause injuries to children. In this study a furniture corner guard was developed using thermoplastic polyurethane filament (TPU) and fused deposition modeling (FDM) 3D printing. First, the energy-absorption performance of cylindrical specimens with different printing parameters (infill pattern, filament hardness, and printing speed) was analysed using a quasi-static compression test. The experimental results showed that among the three infill patterns, the honeycomb pattern had the best energy-absorption performance, the gyroid pattern had the middle energy-absorption performance, and the linear pattern had the worst energy-absorption performance. The energy-absorption performance of the cylindrical specimen gradually increased with decreased filament hardness and decreased printing speed. Then, the furniture corner guard with buffer airbag was designed by SolidWorks software, and the prototype was additively manufactured using honeycomb infill pattern, Shore A 75 TPU filament, and 20 mm/s printing speed. The 3D-printed furniture corner guard had a smooth outer surface, free of print defects, and was custom-designed to fit the size and shape of the furniture corner to ensure a tight fit. The energy-absorption performance of 3D-printed furniture corner guard was about 90% in comparison to injection-molded PFC.

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Keywords: TPU filament; Furniture corner guards; FDM; Additive manufacturing

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INTRODUCTION

Thermoplastic polyurethane (TPU) has a wide range of applications in 3D printing, benefiting from its excellent physical and chemical properties (Ding *et al.* 2022). TPU is an $(AB)_n$ block linear polymer consisting of flexible soft segments and rigid hard segments, a structure that allows TPU to have both the high elasticity of rubber and the high strength of plastic (Deng *et al.* 2023). Because the soft and rigid segments of TPU materials can be composed of different materials, by controlling the composition and ratio, TPU materials with different hardness can be synthesised, thus enabling TPU to be used in 3D printing for the manufacture of products with different properties (Han *et al.* 2022). The softness and elasticity of the TPU material makes it ideal for 3D printing flexible parts such as shoe soles, seals, shock absorbers, *etc.* These parts are capable of undergoing stresses when subjected to force, thus providing protection or cushioning (Feng *et al.* 2022).

Fused deposition modeling (FDM) is one of the most widely used 3D printing processes. Its characteristics include a simple principle of processing, high printing efficiency, and low material cost. Furniture corners are the areas most likely to be damaged by collisions or to cause injuries to children. 3D-printed furniture corner guards are a practical and innovative solution that is particularly well suited to protecting furniture corners as well as preventing injuries to children from collisions. Due to the personalised nature of 3D printing, furniture corners can be custom designed according to their size and shape to ensure a tight fit (Huang *et al.* 2022). Compared with traditional plastic processing, 3D-printed furniture corner guards do not require moulding, which saves time and cost in product development (Liu *et al.* 2021). The TPU filament is also an ideal material for making furniture corner guards due to its excellent elasticity, abrasion resistance, and impact resistance (Li *et al.* 2022). In this study, FDM 3D printing and TPU filament were applied to the additive manufacturing of furniture corner guards, and through reasonable structural design and optimisation of printing parameters, safe and beautiful furniture corner guards were produced, providing a reference for the rapid development of similar products (Chen *et al.* 2022). This work integrates the advantages of personalized customization of 3D printing technology into the field of home products, which can thoroughly change the traditional mode of design, production consumption of home products, and provide users with highly flexible and creative solutions.

EXPERIMENTAL

Materials

The TPU filament with a diameter of 1.75 mm (Black, Melting point 210 °C, Bambu Lab, Shenzhen, China) was used for additive manufacturing by FDM.

Specimen Preparation

To investigate the energy-absorption performance of the FDM 3D-printed TPU model, a cylindrical specimen was designed in this study with the following dimensions: diameter of 20 mm and height of 30 mm. Solidworks software (Dassault Systemes, Education Version 2016, Paris, France) was applied to draw the 3D model of the cylindrical specimen, and it was exported as an STL file. Subsequently, the STL file was loaded into Cura software (Ultimaker, Cura 4.2.1, Utrecht, Netherlands) for slicing to generate G-code processing data. Finally, TPU filament was applied to fabricate the cylindrical specimen through an FDM 3D printer (0.4 mm nozzle diameter, X-Y-Z printing, Bambu Lab, Shenzhen, China). The printing process and machinery is shown in Fig. 1.

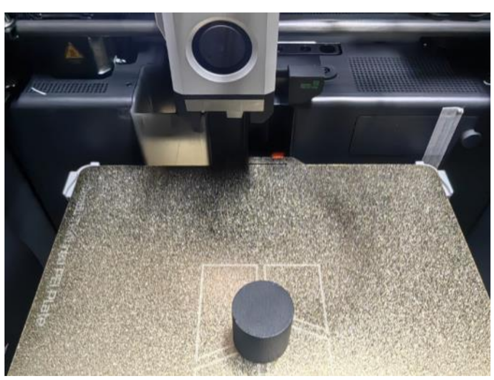

Fig. 1. The printing process and machinery

Energy-absorption Performance

A quasi-static compression experiment on the energy-absorption performance of cylindrical specimens was conducted using a universal mechanical testing machine (20 kN, AG-X, Shimadzu, Kyoto, Japan) with a loading speed of 2 mm/min. The experiment was conducted at 20 °C (Hu *et al.* 2021). Energy-absorption performance is a measure of flexible products in the compression of plastic deformation and absorption of energy indicators. The selected parameters of this experiment were the total energy-absorption value (E_A) and the specific energy-absorption value (S_{EA}). The total energy-absorption value (E_A) is used to characterise the sum of energy absorbed by the cylindrical specimen in compression to a compact state, which is calculated by integrating the area of the shaded area under the stress-strain curve (shown in Fig. 2). The specific energy-absorption value (S_{EA}) is used to characterise the energy-absorption capacity of the cylindrical specimen per unit mass, which is calculated by the ratio of the total energy-absorption (E_A) to the mass of the cylindrical specimen (Mo *et al.* 2022).

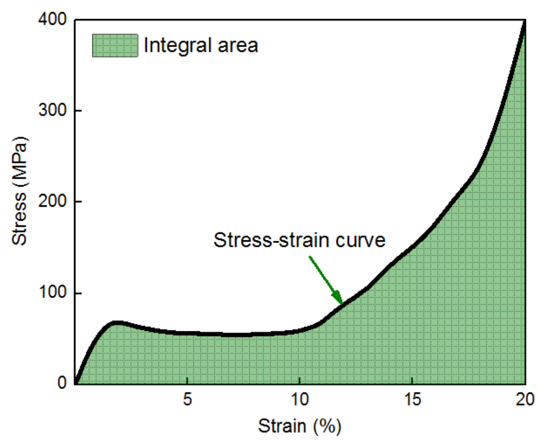

Fig. 2. Compression stress-strain curve

RESULTS AND DISCUSSION

Influence of Infill Patterns on Energy-Absorption Performance

The energy-absorption performance of cylindrical specimens (shown in Fig. 3) with different infill patterns (linear, honeycomb, and gyroid) was tested, and the results are shown in Fig. 4. In FDM 3D printing, the infill pattern not only determines the internal structure of the specimen, but it also directly affects its energy-absorption performance. Linear pattern consists of multiple parallel lines on the plane. This pattern has faster printing speed, but it has poor performance in energy-absorption, because its internal structure is relatively simple. It lacks sufficient support to disperse the load, mainly relying on the elastic deformation of the TPU filament itself to absorb the energy (Hu *et al.* 2024). Thus, the linear pattern exhibited the lowest E_A and S_{EA} values and the worst performance in energy-absorption. The honeycomb pattern consists of multiple congruent hexagons in the plane, which are connected to the sidewall shells of the 3D-printed model, and the hexagons are connected to each other, so there are more cross-structures, which can effectively disperse the load and absorb the energy (Qi *et al.* 2023). Thus, the honeycomb pattern had the highest E_A and S_{EA} values and the best performance in energy-absorption. The gyroid pattern has triple rotational symmetry in space, in which the unique configuration of a minimal amount of surface makes the overall specimen's structure possess larger porosity and better energy-absorption, so the E_A value of gyroid pattern was higher than that of linear pattern and lower than that of honeycomb pattern. The S_{EA} value of gyroid pattern was also lower than that of honeycomb pattern because the gyroid pattern consumes more material and has more mass at the same filling density. Thus, the energy-absorption performance of gyroid pattern was in the middle.

Fig. 3. Schematic diagram of infill patterns

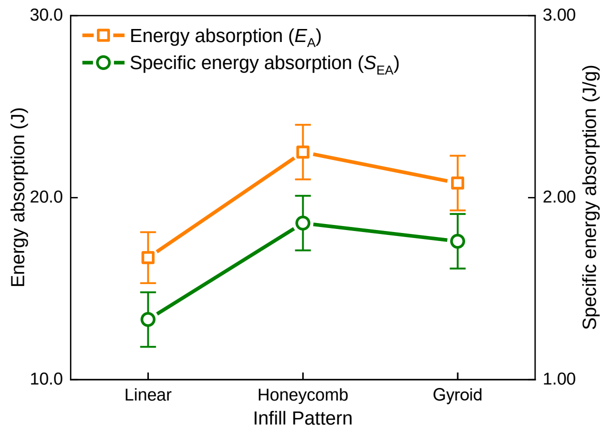

Fig. 4. Influence of infill patterns on energy-absorption performance

Influence of Filament Hardness on Energy-Absorption Performance

The energy-absorption performance of cylindrical specimens under different filament hardnesses (low-hardness, medium-hardness, and high-hardness) was tested, and the results are shown in Fig. 5. Low-hardness (Shore A 75) TPU filament has the characteristics of softness, high elasticity, and strong deformation ability. Its molecular chain flexibility is high, such that it can release thermal energy through the internal friction generated when the molecular chain is stretched and rebounded to achieve the dissipation of compression energy (Li and Hu 2023). Thus, the cylinder specimen printed by low-hardness TPU filament has the best energy-absorption performance. High-hardness (Shore A 95) TPU filament is close to a rigid material with a weak deformation ability (Wang *et al.* 2022). Due to the rigidity of its molecular chain, the molecular chain movement cannot be converted and release energy, mainly through the expansion of micro-cracks within the cylindrical specimen to absorb energy, so the cylindrical specimen printed by high-hardness TPU filament had the worst energy-absorption performance. Medium-hardness (Shore A 85) TPU filament has both elasticity and rigidity characteristics, and moderate deformation ability. The cylindrical specimen printed by medium-hardness TPU filament can both absorb energy and provide a certain degree of rigid support, and the rigidity of its molecular chain is greater than that of low-hardness filament, so its energy-absorption performance was in the middle (Xia *et al.* 2024).

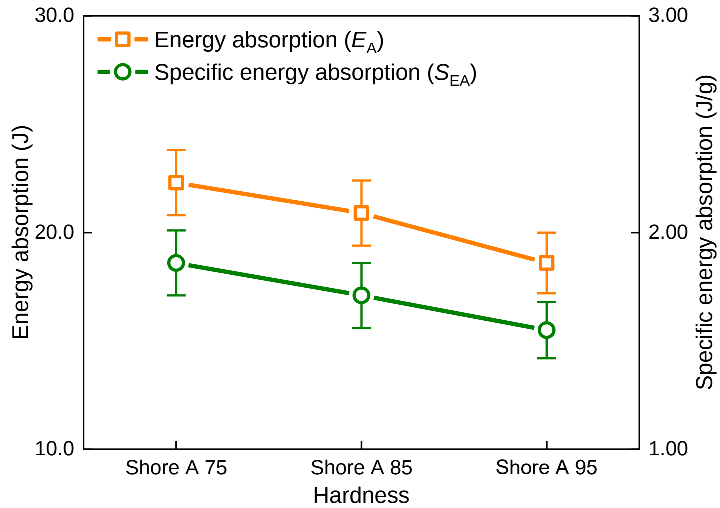

Fig. 5. Influence of filament hardness on energy-absorption performance

Influence of Printing Speed on Energy-absorption Performance

The energy-absorption performance of cylindrical specimens were tested at different printing speeds (20, 40, and 60 mm/s), and the results are shown in Fig. 6. In the compression loading process, the slip of adjacent layers of filaments due to shear force is the main cause of the destruction of cylindrical specimens. As the printing speed decreases, the molten filament has enough time to flow and fuse on the surface of the solidified filament, which promotes the adhesion between adjacent layers of filaments to be more tightly bonded, so the cylindrical specimen is not easy to be destroyed in compression, and thus more energy can be absorbed (Wang *et al.* 2023). When the printing speed increases, the flow and fusion time of adjacent layers of filaments is insufficient, which leads to the gap defects between the layers, and the interlayer separation easily occurs during compression, as well as the energy-absorption performance of the cylindrical specimen decreases (Yang *et al.* 2022).

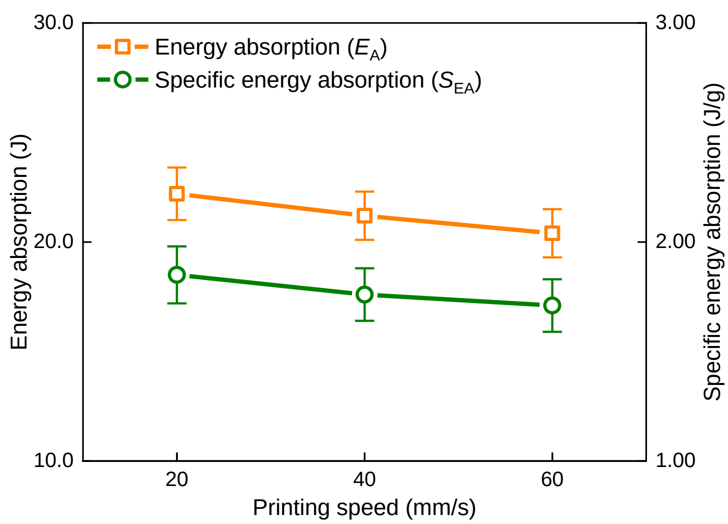

Fig. 6. Influence of printing speed on energy-absorption performance

DESIGN AND ADDITIVE MANUFACTURING

3D Model Design

The dimensions of the furniture corner were measured by vernier caliper, and the 3D model of furniture corner guard (shown in Fig. 7) was designed in SolidWorks software based on the measured dimensions. To solve the problem of lack of buffer structure in the existing furniture corner guard, a drum-shaped buffer airbag was designed in the sharp corner of the furniture corner guard in this design scheme. Except for the buffer airbag area, the outer shell of the furniture corner guard was designed as a thin-walled structure with a thickness of 2 mm (Yu *et al.* 2023).

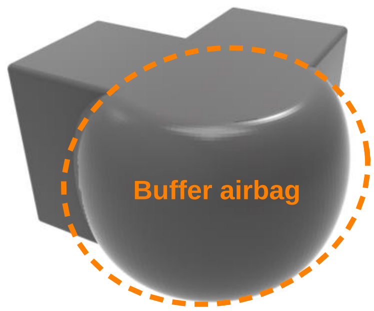

Fig. 7. 3D model of furniture corner guard

Slicing Process

The STL file of the furniture corner guard was imported into Cura software for slicing, and the placement of the corner guard was adjusted so that the top plane of the corner guard fit on the printing platform (shown in Fig. 8). This placement does not create a support structure, which ensures the print quality of the prototype and saves manufacturing time and material costs (Zhu *et al.* 2024).

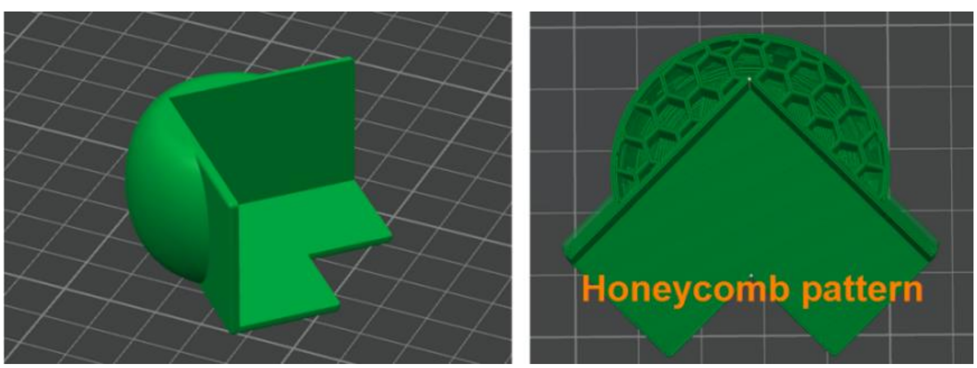

Fig. 8. Placement of furniture corner guard

The main printing parameters were set, with reference to the experimental results above. The infill pattern was set to honeycomb (shown in Fig. 8), and the printing speed was set to 20 mm/s. Taking into account the protective performance and printing cost factors, the layer height was set to 0.2 mm, the infill density was set to 20%, the printing temperature was set to 220 °C, the wall thickness was set to 1.2 mm, the printing flow rate was set to 100%, and the hot bed temperature was set to 65 °C (Yu and Wu 2024).

Additive Manufacturing

The furniture corner guard was fabricated using low-hardness (Shore A 75) TPU filament through an FDM 3D printer. The total 3D printing time of the furniture corner guard was 16 min, and the total material consumption was 28 g, of which 0 g of the support material had to be peeled off, resulting in a material utilisation efficiency of nearly 100%. A 3D-printed prototype of the furniture corner guard is shown in Fig. 9. It had a smooth outer surface and no printing defects.

Fig. 9. 3D-printed prototype of the furniture corner guard

Installation Method

The 3D-printed furniture corner guard can be installed on the furniture corner by double-sided tape adhesion, the double-sided tape is pasted on the inner side of the furniture corner guard shell, which fits the surface of the furniture corner, and the installation schematic is shown in Fig. 10.

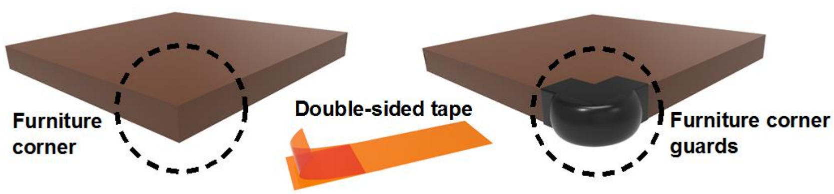

Fig. 10. Installation schematic

APPLICATION ADVANTAGES

Compared with the furniture corner guard made of PVC and injection moulding process sold in the market today, the 3D-printed furniture corner guard has the following application advantages: (1) The 3D-printed furniture corner guard is made from low-hardness TPU filament, a material that is softer than PVC and therefore has better energy-absorption performance and better protection for children when bumped; (2) The existing furniture corner guard lacks a buffer structure, while the 3D-printed furniture corner guard is designed with a buffer airbag, and the buffer airbag uses a low-density (20%) honeycomb structure inside, which has both better energy absorption performance and better resilience, facilitating the rapid recovery of the airbag after a collision; (3) The 3D-printed furniture corner guard has the characteristics of personalised customisation, not only for the actual size of the furniture custom design, but also for the style of the furniture personalised design, for example, for Chinese furniture, you can incorporate traditional Chinese patterns into the design.

CONCLUSIONS

1. The energy-absorption performance of cylindrical specimens with different printing parameters (infill pattern, filament hardness, and printing speed) was analysed by quasi-static compression testing. The experimental results showed that the honeycomb pattern had the best energy-absorption performance, the gyroid pattern had the middle energy-absorption performance, and the linear pattern had the worst energy-absorption performance. The energy-absorption performance of the cylindrical specimens gradually increased with the decrease of filament hardness and the decrease of printing speed.
2. The furniture corner guard with buffer airbag was designed by SolidWorks software, and the prototype was additively manufactured using honeycomb infill pattern, Shore A 75 TPU filament, and 20 mm/s printing speed. The 3D-printed furniture corner guard has a smooth outer surface, free of print defects, and is custom-designed to fit the size and shape of the furniture corner to ensure a tight fit.
3. This work integrates the advantages of personalized customization of 3D printing technology into the field of home products, which can thoroughly change the traditional mode of design, production consumption of home products, and provide users with highly flexible and limitless creative solutions.

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