

Structural Toughness Enhancement Method for Material Extrusion-Based 3D-Printed Model: A Rigid Shell-Flexible Infill Composite Structure

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This study addressed the problem of poor structural toughness of material extrusion-based (MEX) 3D printing polylactic acid (PLA) models and expanded the application of 3D printing technology. A new structural toughness enhancement method was proposed to improve the structural toughness of MEX 3D-printed models by constructing a rigid shell-flexible infill composite structure. Rectangular specimens were designed using SolidWorks software, and the structural toughness of the rigid specimens and rigid shell-flexible infill specimens were tested using three-point bending test and Charpy impact test. The deflection, bending strain energy, and impact strength of the rigid shell-flexible infill specimens were larger than those of the rigid specimens. The enhancement percentages were 103%, 306% and 293%, respectively, indicating that the rigid shell-flexible infill specimens had better structural toughness. In contrast to the conventional material modification methods, the structural toughness enhancement method proposed in this study can maintain the strength and stiffness of 3D-printed models while improving their impact resistance and ductility. The products have unique application value in the fields of smart packaging, sports protective gears, and consumer electronic products.

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INTRODUCTION

Polylactic acid (PLA) is a bio-based polyester made by the polymerisation of lactic acid produced by the fermentation of plants such as corn and sugar cane (Feng *et al.* 2022). With the advancement of global carbon neutrality goals, PLA is expected to become a support material to drive the development of the global green economy (Deng *et al.* 2023). As a commonly used consumable in additive manufacturing technology, PLA filament is widely used in education, healthcare, and packaging fields due to its environmental friendliness, ease of use, and low cost (Ding *et al.* 2022). Compared with other commonly used consumables for additive manufacturing, PLA has high strength and stiffness, but its toughness is poor (Chen *et al.* 2022). This is because the PLA main chain consists of ester groups (-COO-) and lacks flexible groups (*e.g.*, the -CH₂- linkage of PE). The strong polarity of the ester group and the steric hindrance of side methyl group result in poor mobility of the PLA molecular chain segments (Han *et al.* 2022). Under the action of external forces, PLA molecular chain has difficulty in absorbing energy through conformational adjustment, and it is easy to break directly (Hu *et al.* 2024). Therefore, the

toughness of PLA filament is poor and the structure is brittle (Huang *et al.* 2022).

Material extrusion-based (MEX) 3D printing is a technology in which thermoplastic filaments are used as raw materials, melted, and extruded through heated nozzles, and deposited layer by layer according to a predetermined path to form a physical prototype (Li *et al.* 2023). The structural toughness of a MEX 3D-printed model refers to its ability to resist fracture when subjected to force, and it is an important indicator for determining the reliability and service life of 3D-printed models (Liu *et al.* 2021). Due to the poor toughness of PLA, the structural toughness of models made by PLA filament and MEX technology is usually poor. To solve this problem, the conventional method is to modify the PLA filament physically or chemically to improve its toughness, such as blending resins (*e.g.*, polycaprolactone), adding plasticisers (*e.g.*, polyethylene glycol), or introducing fillers (*e.g.*, wood fiber). When the toughness of the PLA filament is improved, the structural toughness of the model 3D printed from it can also be enhanced (Mo *et al.* 2022).

Different from conventional material modification methods, this study proposes a new structural toughness enhancement method for MEX 3D-printed models, which improves the structural toughness of 3D-printed models by constructing a composite structure of rigid shell-flexible infill. The method combines the respective advantages of rigid and flexible materials, which can maintain the strength and stiffness of the 3D-printed model and effectively improve its structural toughness, so that it can show its unique application value in the fields of smart packaging, sports equipment, and consumer electronic products (Hu *et al.* 2021). To achieve composite printing of rigid materials (PLA) and flexible materials (TPU), this study used the automatic material system (AMS) technology of the Bambu Lab 3D printer. This technology has only gradually matured in recent years and has strong novelty. At present, there is relatively little research on the mechanical properties of models based on such multi material 3D printing technology.

This study employed three-point bending tests and Charpy impact tests to evaluate the toughness of 3D-printed rigid specimens and rigid shell-flexible infill specimens under quasi-static and dynamic loading conditions, respectively. The three-point bending tests characterized the flexural properties and fracture toughness of specimens under quasi-static loading, while the Charpy impact tests assessed their energy absorption capacity and impact toughness under dynamic impact conditions. The combination of these two testing methods can comprehensively analyze the structural toughness of rigid shell-flexible infill specimens under different working conditions, filling the gap in existing research on multi-condition testing of plastic structural toughness and providing experimental evidence for optimizing the toughness of 3D-printed models. A future research goal of this work is to apply the ‘rigid shell-flexible infill’ concept in the case of PLA compounded with compatibilised cellulose nanofibers of some type (*e.g.*, surface-modified CNC).

EXPERIMENTAL

Rigid Shell-flexible Infill Composite Structure

Typically, MEX 3D-printed models consist of two parts: shell and infill. For the special structure of MEX 3D-printed models, this study innovatively proposes a rigid shell-flexible infill composite structure printing method, *i.e.*, the shell of the model is printed with rigid material to provide the required structural strength and deformation resistance; the infill of the model is printed with flexible material, which absorbs energy through its

elastic deformation and achieves the enhancement of the structural toughness (Yang *et al.* 2022). Figure 1 shows a cutaway view of the MEX 3D printed model, where the black area is the flexible infill and the white area is the rigid shell.



Fig. 1. Schematic of rigid shell-flexible infill composite structure

Materials

For the 3D-printed model with the rigid material of PLA filament (1.75 mm diameter, white, Bambu Lab, Shenzhen, China), the chosen flexible infill material was TPU filament (1.75 mm diameter, black, Bambu Lab, Shenzhen, China). This is because the polyester/polyether soft segment of TPU is easy to physically entangle with the PLA molecular chain, and the carbamate group (-NHCOO-) in the hard segment of TPU can form hydrogen bonding with the ester group (-COO-) of PLA. As a consequence, there is a better adhesion between the TPU filament and the PLA filament (Qi *et al.* 2023).

Specimen Preparation

The rectangular specimen (160 mm in length, 15 mm in width, and 8 mm in height) was designed using SolidWorks software, and the 3D model of the rectangular specimen was exported to an STL file, which was subsequently imported into Cura software for slicing. A MEX 3D printer (X1-C, nozzle diameter 0.4 mm, Bambu Lab, Shenzhen, China) was used for additive manufacturing of the G-code files obtained from the slicing process.

The experimental specimens were divided into two types: rigid (specimen number: A1~A6) and rigid shell-flexible infill (specimen number: B1~B6), as shown in Fig. 2. The rigid specimens were printed with PLA filament only, and the rigid shell-flexible infill specimens were printed with PLA filament and TPU filament. To control the experimental variables, the same dimensional and slicing parameters were used for both specimens, and the specific slicing parameters were as follows: extrusion temperature of 220 °C, print speed of 60 mm/s, grid infill, infill rate of 20%, hot bed temperature of 60 °C, layer height of 0.2 mm, and extrusion rate of 100% (Li *et al.* 2022).

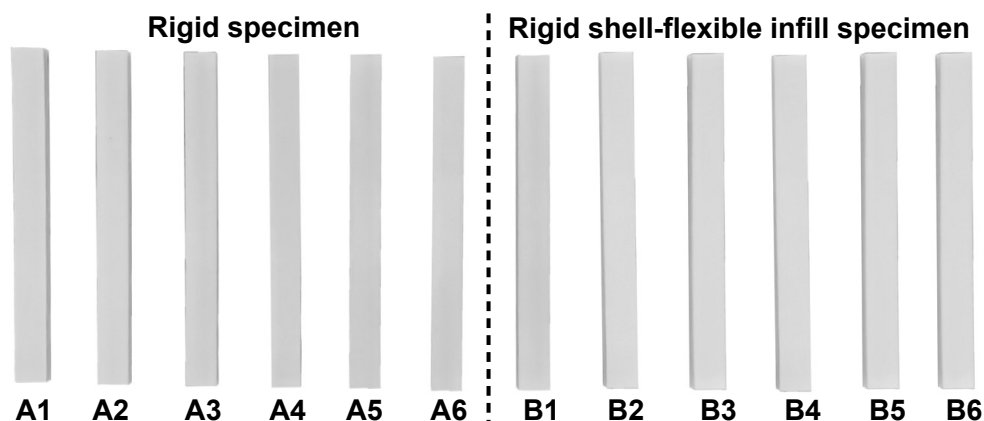


Fig. 2. Experimental specimens

To achieve the composite printing of rigid material (PLA) and flexible material (TPU), this experiment used the automatic material system (AMS) technology of a Bambu Lab 3D printer. The principle of AMS is as follows: the AMS system identifies information such as the material, colour and specification of the filament through the magnet sensor. During the printing process, when the filament needs to be changed according to the requirements of the slicing setup, the AMS system will automatically withdraw the current filament and quickly switch to the next one (Wang *et al.* 2022). At this time, the newly switched filament is accurately transported to the nozzle through the conveyor, and the whole switching process is rapid and accurate without manual intervention, which greatly improves the printing efficiency.

Performance Test

To investigate the effect of rigid shell-flexible infill composite structure on the structural toughness enhancement of MEX 3D-printed models. In this study, it was evaluated by three-point bending test and Charpy impact test.

The three-point bending test was used to evaluate the strength, stiffness and toughness of plastics under bending loads and is carried out on a universal mechanical testing machine (AG-X, 20 kN, Shimadzu, Kyoto, Japan) at 20 °C. The principle of the three-point bending test is to place a rectangular specimen on two supports and apply a load to the specimen through a loading indenter (Wang *et al.* 2023). Under the bending load, the specimen will be deformed in bending. Until the model breaks and destroys, the load F and deflection δ applied to the specimen by the loading indenter during this process are measured, and the bending strain energy of the specimen (U) can be calculated by the following formula.

$$U = \int_0^{\delta} F d\delta \quad (1)$$

The Charpy impact test was used to evaluate the toughness and resistance to fracture of plastics under high speed impact, and it was carried out on a Charpy impact test machine (J8-100, Zhongchuang, Jinan, China) at 20 °C (Xia *et al.* 2024). The pendulum was lifted from the vertical position at a certain angle α , so that the pendulum would fall freely and break the rectangular specimen under the action of kinetic energy. After breaking the specimen, the pendulum used the residual energy to lift the arm of the device up to a certain angle β . According to β , the power W consumed by the pendulum impacting the specimen can be calculated, and then divided by the cross-sectional area of the specimen can be obtained from the impact strength I of the material (unit kJ/m²), as follows,

$$I = \frac{Pl (\cos \beta - \cos \alpha)}{A} \quad (2)$$

where P is the weight of the pendulum, l is the length of the pendulum, and A is the cross-sectional area of the specimen.

RESULTS AND DISCUSSION

Comparison of Bending Performance

Comparing the bending performance of rigid specimens (A1, A2, A3) and rigid shell-flexible infill specimens (B1, B2, B3), the test results are shown in Figs. 3 and 4. The

average values of deflection and bending strain energy of specimen B1, B2, and B3 are 22.4 mm and 6.29 J, respectively, which are larger than the average values of specimen A1, A2, and A3 (11.10 mm and 1.55 J), and the enhancement rates are 102% and 306%, respectively. This indicates that the structural toughness of the rigid shell-flexible infill specimens was higher. This is because the failure mode of the rigid specimens was brittle fracture, while the failure mode of the rigid shell-flexible infill specimens was delamination peeling and local buckling. For example, in 3D-printed packaging padding, padding printed with the rigid shell-flexible infill produces higher ‘bending strain energy’ and is safer than rigid padding. When the rigid shell is stressed and cracked, the flexible infill forces the crack to expand along the adhesive interface of the rigid-flexible materials, which increases the length of the fracture path and forms the delamination peeling phenomenon, thereby avoiding the brittle fracture caused by stress concentration (Yu *et al.* 2023). At the same time, the flexible infill locally flexes under the bending load, forming a ‘fold’ structure, which improves the plastic deformation capacity of the specimens, resulting in a significant increase in the structural toughness of the specimens.

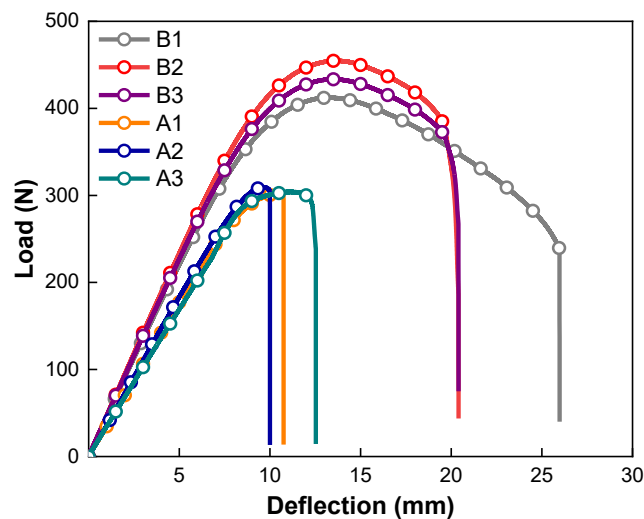


Fig. 3. Load-deflection curve

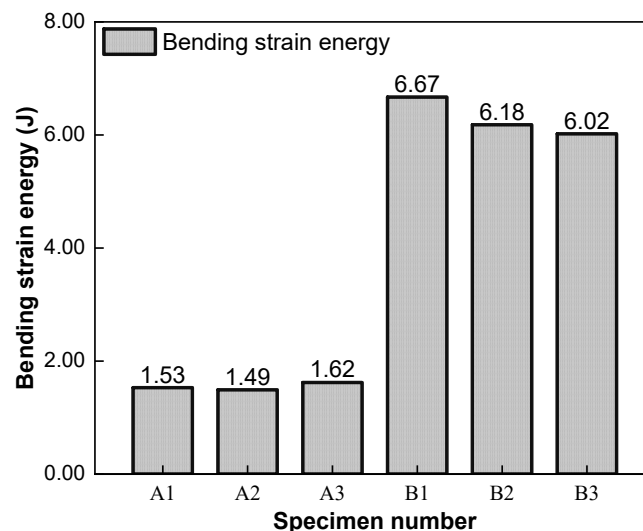


Fig. 4. Comparison of bending strain energy

Comparison of Impact Resistance

Comparing the impact resistance of rigid specimens (A4, A5, A6) and rigid shell-flexible infill specimens (B4, B5, B6), the test results are shown in Fig. 5. The average value of the impact strength of specimen B4, B5, and B6 was 4.91 kJ/m^2 , which was larger than the average value of specimen A4, A5, and A6 of 1.25 kJ/m^2 , and the enhancement percentage was 293%. This indicates that the structural toughness of the rigid shell-flexible infill specimens was better. This is because the failure mode of the rigid specimens was brittle fracture, while the failure mode of the rigid shell-flexible infill specimens was ductile delamination. From the macroscopic point of view, when the pendulum impacts, the flexible infill absorbs the impact energy through plastic deformation, which reduces the centralised transfer of stresses to the rigid shell, thus avoiding brittle fracture of the specimens (Yu and Wu 2024). From the microcosmic point of view, the molecular chain breakage caused by several mutually bonded PLA filaments under the impact force is the main reason for the destruction of the rigid specimens. In contrast, the TPU molecular chains in the rigid shell-flexible infill specimens produced chain segment slip under stress, which dissipated energy through inelastic deformation, resulting in a significant increase in the structural toughness of the specimens (Zhu *et al.* 2024).

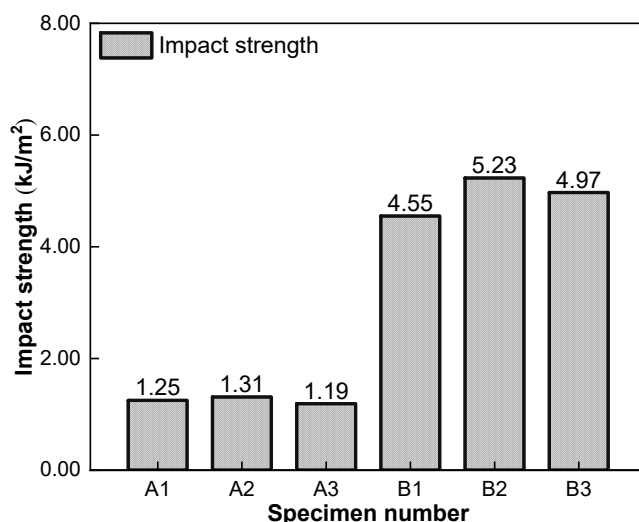


Fig. 5. Comparison of impact strength

POSSIBLE FUTURE WORK

With the continuous development of 3D printing technology, cellulose and its derivatives have gradually been applied to the preparation of 3D printing materials and the improvement or enhancement of printed product performance. This study proposes a new method for enhancing the structural toughness of MEX 3D-printed models and aims to extend this research approach to cellulose-based 3D printing materials. The objective of such research is to apply the 'rigid shell-flexible infill' concept in the case of PLA compounded with compatibilised cellulose nanofibers of some type (*e.g.*, surface-modified CNC).

CONCLUSIONS

1. To solve the problem of poor structural toughness of MEX 3D-printed PLA models, this study proposed and demonstrated a new structural toughness enhancement method by constructing a composite structure of rigid shell-flexible infill to improve the structural toughness of 3D-printed models.
2. The structural toughness of rigid specimens and rigid shell-flexible infill specimens were tested using three-point bending test and Charpy impact test. The results showed that the deflection, bending strain energy, and impact strength of the rigid shell-flexible infill specimens were larger than those of the rigid specimens, and the enhancement percentages were 103%, 306% and 293%, respectively, which indicates that the structural toughness of the rigid shell-flexible infill specimens was higher.

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