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BRIEF ORIGINAL

Use of wood powder and adhesive as a mixture for 3D printing

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Abstract In recent years there has been much development in the field of additive manufacturing technologies, but only a few attempts have been made to use natural materials like wood for 3D printing. In this research different ratios of wood powder were used as a component in adhesive mixtures for 3D printing. Polyvinyl acetate and urea–formaldehyde adhesives were used as binders, and the optimum mixture was determined by measuring the corresponding extrusion forces. Simple blocks were 3D printed and the bending properties of these blocks were investigated. The bending strength depended on the amount of wood powder in the mixture and on the type of adhesive.

1 Introduction

Additive manufacturing (AM), also referred to as 3D printing, involves the manufacturing of a part by depositing material layer-by-layer, as opposed to conventional processes such as subtractive processes (milling), formative processes (casting or forging), and joining processes (welding) (Conner et al. 2014). AM methods offer more “design freedom”, including the possibility of constructing geometries that cannot be fabricated by any other means, creating functional parts without the need for assembly or specialized tools, moulds, etc. (Henke and Treml 2013). Different techniques with their own processing capabilities, advantages, and limitations are available for different materials to produce final products with different properties (Hopkinson et al. 2006, Conner et al. 2014). 3D printers themselves can range from desktop printers to printers capable of producing parts that are measured in several metres (Conner et al. 2014). AM is competitive with conventional production when pieces of high complexity need to be produced in small batches or when unique pieces/prototypes are produced (Henke and Treml 2013).

A number of materials are available for 3D printing. These range from polymers (polyamide, acrylonitrile butadiene styrene (ABS), polylactic acid (PLA), polyvinyl alcohol (PVA)) to even ceramic, gypsum, metals (stainless steel, gold and silver, titanium) or even concrete (Henke and Treml 2013). However, the material properties, such as strength, electrical and thermal conductivity, and optical transparency are typically inferior compared to their conventionally manufactured counterparts due to the anisotropy caused by the layer-by-layer approach (Ivanova et al. 2013). One of the factors that limit the expansion of 3D printers is the price of the material (e.g., expensive UV curing resins, materials for laser sintering) and the synthetic origin of most of the materials (possibly harmful for the environment). Some examples of the use of natural materials such as wood in combination with plastics and gypsum (Henke and Treml 2013) or possibilities for the production of multifunctional nanocomposites (Campbell and Ivanova 2013) have already been presented. If natural materials were to be used, the prices, the hazard represented by synthetic materials and carbon footprint of 3D printed products could be reduced.

Wood is a natural, organic material that is widely available in the form of wood residues, which can be milled into smaller fractions or fine wood powder, and used as a component in 3D printing with conventional plastic materials, natural adhesives, or with gypsum, cellulose, sodium silicate, and cement as a binder (Henke and Treml

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2013). Due to the low density of such as products, they could be used as containers of more complex forms, for the making of moulds for laminated furniture, or as supports for the making of furniture in combination with veneers and foils.

The aim of this study was to incorporate wood powder as a material for 3D printing. The optimal mixture of wood powder and adhesive, as well as printing parameters were determined. Finally, the mechanical properties of the 3D printed parts were determined.

2 Materials and methods

The research was performed in two stages: the first stage consisted of the optimization of the mixture of wood powder and adhesive for extrusion, and measurements of the force needed for the extrusion of each mixture. The extrusion force measurements were used to calculate the air pressure which is needed to ensure that material extrusion occurs in the second stage. The second step was the 3D printing of simple blocks and the testing of their bending properties.

2.1 Mixtures of wood powder and adhesive for 3D printing

Two commercially available adhesives, a PVAc adhesive (Mekol D3, Mitol d.d. Slovenia) and an UF adhesive (W-Leim 3000, Dynea Austria GmbH, Austria), were used to prepare mixtures with different ratios of wood powder and adhesive (12.5, 15, 17.5, 20, 22.5 and 25 %). Wood powder from beech wood (*Fagus sylvatica* L.) was prepared by grinding. Only the fraction whose particles passed through a sieve with mesh openings of 0.237 mm was used. Fresh mixture of wood powder and adhesive was prepared for each block just before printing and the printing lasted 11 min.

2.2 Extrusion force measurements

The material for 3D printing needs to be sufficiently flowable to ensure homogenous flow and adequate adhesion to the previous layer, but viscous enough so that it does not spread when deposited in layers. The aim of the first part of the research was to define the optimum ratio between wood powder and adhesive in order to achieve a mixture with sufficient flow while simultaneously using as much wood as possible. The force needed for the extrusion of different mixtures was measured by means of a universal testing machine with a modified grease gun and piston (Fig. 1a). The force needed to move piston and extrude the mixture of wood powder and adhesive through a 3 mm nozzle was measured. Three replications were performed for each mixture.

2.3 3D Printing

A home-made delta type 3D printer (fixed table and moving extruder) was used for the manufacturing of the specimens. The extruder was made from a modified grease gun, with an interchangeable nozzle that had several different diameters. The container was filled with a mixture of wood powder and adhesive, the piston was inserted behind the material, and the container was then pressurized using compressed air in order to cause extrusion of the material through the nozzle. The pressure of the compressed air was regulated manually with an air pressure regulator according to the viscosity of the different mixtures, and the supply of the compressed air was regulated by a solenoid valve. During extrusion the extruder chamber was pressurized, but during moves without extrusion (i.e., non-printing moves) the air supply was closed and the pressure was released through a release valve in order to prevent oozing of the material. To ensure faster solidification of the printed material, a heated bed with a surface temperature of 80 °C was used.

2.3.1 Printing parameters

A simple block with dimensions of $150 \times 30 \times 8$ mm^3 was used as a model for the 3D printing. The model was sliced into 4 layers, each being 2 mm thick. The coverage of each layer with printed material was set to 85 %. The speed of movement during printing was set to 10 mm/s. A 3 mm nozzle on the extruder was used for printing. The pressure of the supplied compressed air was regulated according to previous extrusion force measurements from 0.05 to 0.4 N/mm^2 in order to ensure constant flow of the extruded material and constant thickness of the printed line. The 3D printed blocks were left to cure on a hot plate having a temperature of 50 °C for 2 h and then left for one week to completely solidify in a standard climate. The bending strength of blocks ($n = 5$) was tested on a Zwick-Roel Z005 universal testing machine. The loading rate was set to 15 mm/min. Actual thickness and widths were measured prior to testing, and the bending strength and modulus of elasticity were determined.

3 Results and discussion

The force needed for extrusion increased with the amount of wood powder in the adhesive mixture (Fig. 2). The trend was similar in the case of mixtures made using both types of adhesive, i.e., the PVAc and UF adhesive. In the case of

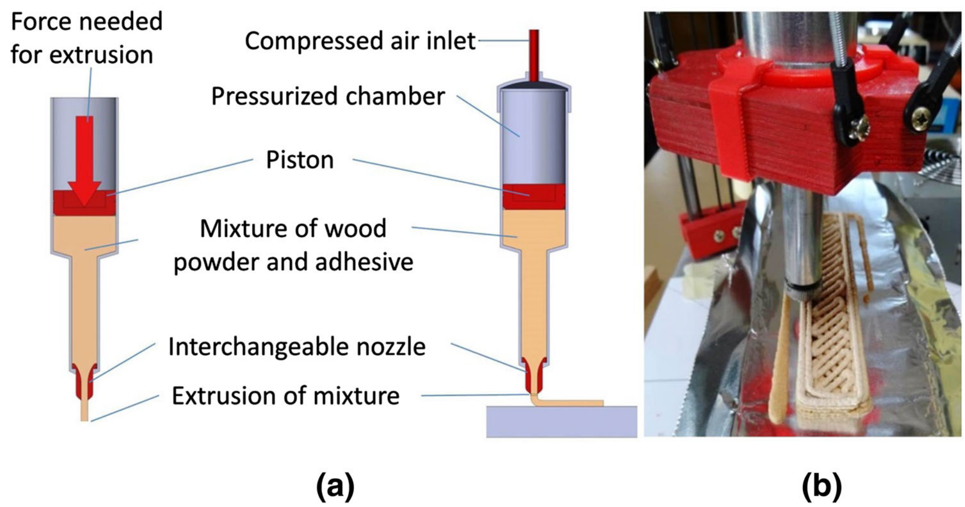

Fig. 1 **a** Test setup for measuring the extrusion force by means of a universal testing machine (*left*) and the test set-up for 3D printing with a pressurized chamber (*right*), **b** 3D printing with a mixture of wood powder and adhesive

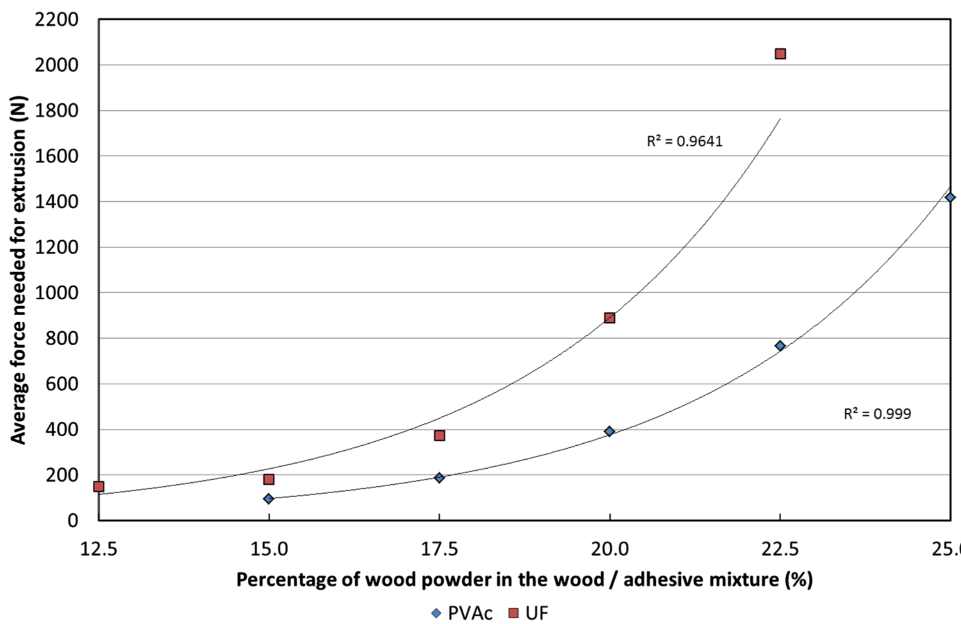

Fig. 2 Extrusion forces for the different mixtures of wood powder and adhesive

the PVAc adhesive the extrusion force was the lowest for the mixture with 15 % of wood powder (96 N), and then increased exponentially to 1416 N for the mixture with a wood powder content of 25 %. The reason for these higher extrusion forces was the higher viscosity of the mixtures, and is similar to the case when wood plastic composites are extruded. In the case of the UF adhesive, the forces needed for extrusion were higher than in the case of the PVAc adhesive for all the prepared mixtures. For the UF adhesive mixture with a wood powder content of 15 %, the extrusion force was 182 N, i.e., 89 % more than for the mixture made with PVAc adhesive.

For the final 3D printing, PVAc mixtures with wood powder percentages of 17.5 and 20 %, and UF mixtures with percentages of 15 and 17.5 % were chosen.

It was found that the bending properties of the 3D printed blocks depended to a high degree on the type of adhesive used (Fig. 3). The measured bending strength and stiffness were much higher in the case of the UF adhesive, and were not affected by the amount of wood powder in the mixture probably because the UF adhesive itself had a high strength and the particles did not contribute significantly to the strength of finally cured specimens. The blocks made using PVAc exhibited lower strength and stiffness, which depended on the amount of wood powder in the PVAc adhesive mixture.

During curing, shrinking of both the adhesives used occurs due to water removal. So it was expected that the 3D printed blocks would also shrink during the curing phase. The highest shrinkage was in the case of thickness,

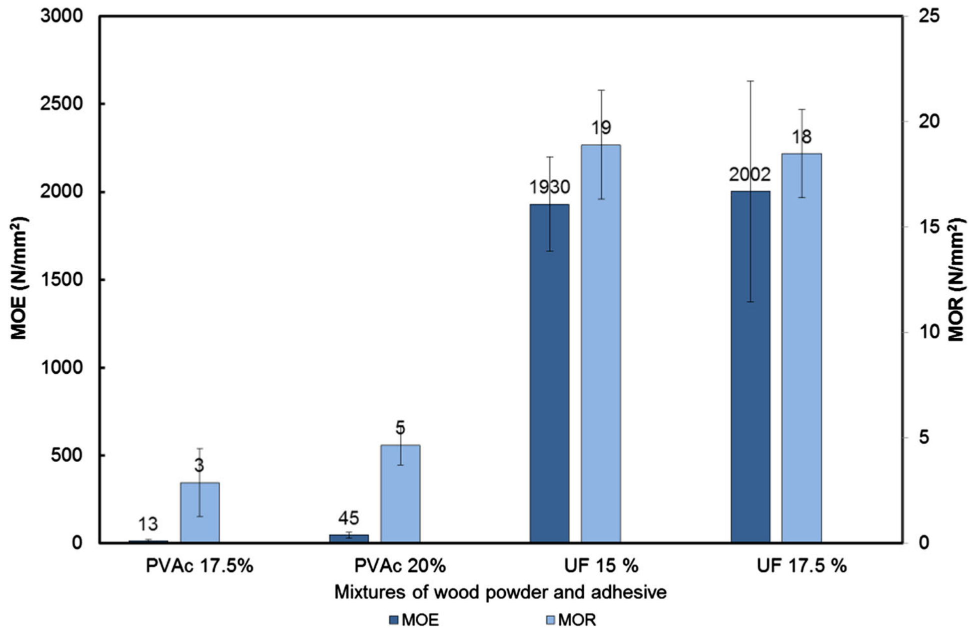

Fig. 3 Average bending strength (MOR) and modulus of elasticity (MOE) for the 3D printed blocks made from different mixtures of wood powder and adhesive (n = 5)

and amounted to 22 % for the UF and 17 % for the PVAc adhesive mixture. Part of this thickness loss is also because of the material flow, since the weight of the top layers forces material in lower layers to flow outward. This means that the models need to be scaled up before 3D printing, in order to ensure that the final dimensions are within the range of the desired dimensions.

4 Conclusion

The results showed that it is possible to use wood powder in mixtures which contain adhesive for 3D printing. The mechanical strength of 3D printed parts from PVAc adhesive mixtures was insufficient and needs to be improved. The 3D printed parts from UF adhesive mixtures showed strength that could be sufficient for use in the case of non-structural applications only. In order to make the technology suitable for a broader range of applications, further optimization of the raw material used and the 3D printing process itself needs to be performed. For faster solidification of the products the use of hot melt adhesives and adhesives which react with air humidity and/or a second component is optional, but for this purpose a more complex extruder needs to be developed.

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