European Journal of Wood and Wood Products (2018) 76:797–799
https://doi.org/10.1007/s00107-017-1274-8

BRIEF ORIGINAL

Liquid Deposition Modeling: a promising approach for 3D printing of wood

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Received: 28 February 2017 / Published online: 7 December 2017

Abstract

Liquid Deposition Modeling is introduced as a promising technology for 3D printing of wood. Specimens were printed using different paste-like suspensions made from ground beech sawdust and methylcellulose dissolved in water. The wood content could be increased up to 89% in dry mass. Physical properties were influenced by binder/water ratio and wood particle size. Shrinkage due to drying was 17.3–20.0%. Density values (r_{12}) lay between 0.33 and 0.48 g/cm^3. Bending strength and modulus of elasticity ranged from 2.3 to 7.4 and from 284.8 to 733.1 N/mm^2, respectively. Density, MOR and MOE increased with increasing viscosity of dissolved methylcellulose and decreased with increasing particle size.

1 Introduction

3D printing or additive manufacturing is a process of making three dimensional solid objects from a digital model. The creation of a 3D printed object is achieved using additive processes: in general an object is created by adding layer-upon-layer of material until the entire object is created. A wide variety of additive processes already exist, for example Stereolithography (SLA), Fused Deposition Modeling (FDM) and Selective Laser Sintering (SLS) (Fastermann 2014). The various processes differ according to the used materials and how the material layers are deposited. Khoshnevis developed the Contour Crafting (CC) for building construction with viscous materials such as concrete or clay. The use of two trowels, a key feature of CC, creates smooth surfaces on the printed objects (Khoshnevis 2002). A more simple technology without troweling tools is called Liquid Deposition Modeling (LDM). It is used for 3D printing of ceramics (e.g., World's Advanced Saving Project, CSP srl, Massa Lombarda, Italy) and food pastes.

In a compound with other materials, wood has already been used for 3D printing. Commercial FDM filaments are available, which contain a certain percentage of wood (Le Duigou et al. 2016). Henke and Treml (2013) investigated the process of the selective activation of thin layers consisting of wooden particles as bulk material and gypsum, methylcellulose, sodium silicate and cement as binding agents. The first attempts to print wood composites by means of LDM are described by Kariz et al. (2016). They used polyvinyl acetate (PVAc) and urea–formaldehyde (UF) adhesives as binder; the amount of wood powder in the 3D printed objects was restricted to 15–20%.

The aim of this study was to achieve a significantly higher percentage of wood. Thus, the economic and ecological advantages of wood can contribute to open up new fields of application for the innovative 3D printing technology. The focus was put on methylcellulose (MC) as binding agent. MC is a cellulose derivative and made from renewable raw materials. It is widely used in the production of adhesives, cosmetics, food, paints and pharmaceuticals, for example, as binding, emulsifying and thickening agent. Variations of binder/water ratio and different wood particle sizes were investigated regarding physical properties.

2 Materials and methods

Air-dry sawdust from beech (*Fagus sylvatica* L.) was ground by a centrifugal mill (Type ZM 1000, Retsch, Germany) and stored at 22 °C and 55% RH. The mixtures were made from fractions of the ground sawdust with two different particle size distributions. Fraction A contained particles, which passed through a sieve with a mesh size of 0.25 mm. For fraction B, the fraction A particles were mixed at a ratio of 1:1 with particles passing the 0.4 mm but not the 0.25 mm

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sieve. Methylcellulose (Carl Roth/Germany, CAS No.: 9004-67-5, viscosity: 3660 mPa s) was used as an additional ingredient, which served both as lubricant and binding agent. The MC powder was added to water (ratio of 1:20 or 1:30). After dissolving and swelling, the gel-like mass was mixed with the ground sawdust.

Finally, three different mixtures were prepared (mass-related values):

M1: MC/water 1:30, MC/wood fraction A 11:89,

M2: MC/water 1:20, MC/wood fraction B 15.5:84.5,

M3: MC/water 1:20, MC/wood fraction A 14.5:85.5.

For the manufacturing of the specimens a standard Cartesian 3D printer with a self-made extruder was used. The paste extruder consists of (1) a cylindrical plastic cartridge with an internal diameter of 27 mm and as an outlet an 8 mm nozzle (see Fig. 1a) with a length of 51 mm and (2) a NEMA 17 linear stepper motor (OMC Corporation Limited/ China, Part No. 17LS19-1684N-200D), which moves a piston towards the outlet by means of a lead screw. Printing was carried out with a traverse speed of 1 mm/s.

To measure the dimensional stability of the mass a special kind of "tower" (Fig. 1b) was printed: external diameter of 40 mm, 11 layers (limited by the cartridge volume of approximately 70 ml), layers 4 mm high (first layer 3 mm for an improved adhesion to the printer bed). The height of the towers was measured by a caliper first immediately after the print and second after drying (60 °C, 5 days) and conditioning (20 °C, 65% RH, 7 days).

The bending specimens with dimensions of 200 mm x 18 mm x 12 mm were printed in 3 layers each 4 mm high (Fig. 1a). After drying (60 °C, 5 days) and conditioning (20 °C, 65% RH, 7 days) bending tests were carried out with a universal testing machine (TIRATEST 28100). The loading rate was set to 0.7 mm/min. Bending strength and modulus of elasticity were determined according to DIN 52186 (1978). For calculation of the density (r_{12}) volume and mass of the broken bending test specimens were measured.

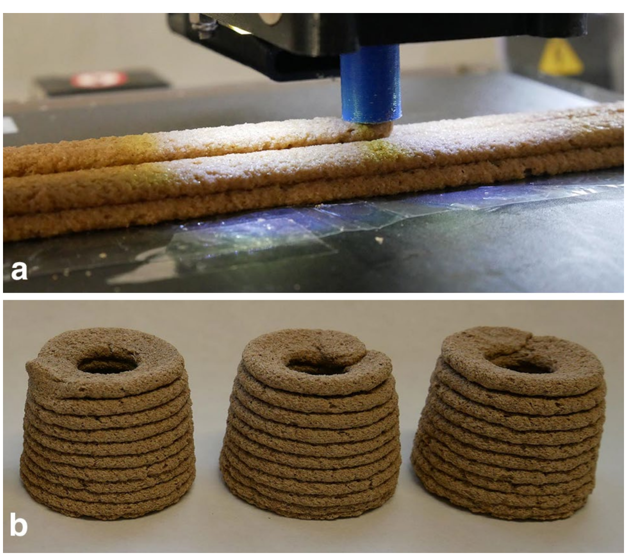

Fig. 1 Printing of bending specimens (**a**) and printed "tower" specimens for measuring dimensional stability after drying (**b**)

3 Results and discussion

One of the fundamental challenges with regard to printing of wood is to combine the transportability of the material during printing process with stability after printing is finished. Fused Deposition Modeling with wood-filled thermoplastics solves this problem by changing the aggregate state from a melted transportable liquid to stable solid. Using the Liquid Deposition Modeling for printing of wood one has to prepare a paste-like suspension, whereby the granular wood material acts as the solid dispersed phase in a liquid dispersion medium, for example dissolved methylcellulose. The resulting paste has a load-dependent behavior: the substance flows like a viscous liquid at high stress and behaves as a rigid body without mechanical load. After this load-dependent liquid/solid state drying transforms the printed object into a load-independent solid state. A possible remoistening, for example, for reasons of recycling, returns the paste into the initial state (if methylcellulose is used as binding agent).

Pre-tests had shown that for each wood fraction there is only a narrow range in which the composition can vary: (1) A phase separation results from a too small MC/water ratio. The thin dispersion medium oozes out of the nozzle and the dispersed wood phase stays in the cartridge. (2) If the wood content is too high, the engine power of the used stepper motor is not sufficient to achieve a load state that leads to a flow behavior of the mixture in the extruder. Kariz et al. (2016) demonstrated that the force needed for extrusion increases exponentially with the amount of wood powder in the adhesive mixture. Furthermore, the dimensions of the paste extruder, in particular the nozzle diameter, likely affect the extrusion force. (3) Due to water removal during drying, shrinking of the printed objects occurs. The higher the water content in the mixture, the larger is the volumetric shrinkage.

For investigating the dimensional stability of the printed objects (I) the height immediately after printing and (II) the height after drying were measured. The first value is a measure of the stability of the paste-like suspension. Kariz et al. (2016) observed material flow, since the weight of the top layers forces material in lower layers to flow outward. The mixtures used in the current study did not show a similar behavior. A height of 43 mm of the digital file generated by means of a 3D modeling software is in contrast to a height of 43.5–44.0 mm of the printed tower specimen (Table 1). A slight increase in height is caused by material expansion due to pressure release after exiting the nozzle (cf. Fig. 1a).

Table 1 Dimensional stability, modulus of rupture (MOR), modulus of elasticity (MOE) and density for 3D printed specimens made from different mixtures of wood (*Fagus sylvatica* L.) and methylcellulose indicated as arithmetic mean and standard deviation (AM ± SD); all test series differ significantly (Mann–Whitney U test, $p < 0.01$) regarding MOR, MOE and density

	Dimensional stability				Bending test			Density (g/cm³)
	n	Height after printing (mm)	Height after drying (mm)	reduction (%)	n	MOR (N/mm^2)	MOE (N/mm^2)	
M1	3	43.5 ± 0.4	36.0 ± 0.8	17.3 ± 1.1	12	2.3 ± 0.4	284.8 ± 46.4	0.33 ± 0.05
M2	5	44.0 ± 0.0	36.1 ± 0.6	18.0 ± 1.3	15	5.1 ± 1.0	546.5 ± 109.7	0.40 ± 0.03
M3	6	43.8 ± 0.4	35.1 ± 1.1	20.0 ± 2.4	15	7.4 ± 1.1	733.1 ± 128.0	0.48 ± 0.03

Volume loss as a consequence of shrinkage can be quantified by the ratio of II/I. Mixture M1 with a wood content of 89% in dry mass showed the highest stability (17.3% height loss). The specimens made of the other mixtures with lower wood content shrank 18% respectively 20%. Kariz et al. (2016) reported similar shrinking values: PVAc mixtures 17% and UF mixtures 22%.

The results of the bending tests and the density measurements varied to a greater extent between the test series. Modulus of rupture (MOR) ranged from 2.3 to 7.4 N/mm² and modulus of elasticity (MOE) from 284.8 to 733.1 N/mm² (Table 1). The values lay between those determined by Kariz et al. (2016) for their PVAc and UF mixtures. The density values ranging from 0.33 to 0.48 g/cm³ are strongly influenced by the specific density of the beech wood used.

By comparing the mixtures M1 and M3 the following can be concluded: the more viscous the dispersion medium, the lower the possible wood content and the higher MOR, MOE and density. The comparison between M2 and M3 shows: the smaller the wood particles in the mixture, the higher MOR, MOE and density.

4 Conclusion

This study showed that Liquid Deposition Modeling is a promising technology for 3D printing of wood. A maximum wood content in the wood paste of almost 90% could be achieved. Since the wood based binding agent methylcellulose was chosen, one could say that the 3D printed mixture consists to 100% of the renewable resource wood. Furthermore, the material is easy and cost-effective to manufacture.

Several physical properties regarding variations of binder/water ratio and different wood particle sizes were investigated. The strength properties, dimensional stability and the spatial resolution is still unsatisfactory, but the initial research findings provide a good basis for further development. It can be assumed that a further reduction of the particle size (1) and a lower water content of the methylcellulose solution (2) lead to increasing MOR and MOE values. A higher wood content (3) results in an enhancement of the dimensional stability and the use of a smaller nozzle (4) improves the spatial resolution of the printed objects. To meet conditions (2), (3) and (4), modifications of the extruder are necessary. Furthermore, an acceleration of the drying and hardening process can be achieved, for example by microwave drying or UV-curing binders.

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