K. Henke, D. Talke, and B. Buschmann, “Einsatz von Holz bei der additiven Fertigung im Bauwesen / Use of Wood in Additive Manufacturing in Construction,” in Proceedings of the 17th Rapid.Tech 3D Conference Erfurt, Germany, 22 -23 June 2021, M. Kynast, Ed., München: Hanser, Carl, 2021, pp. 177–187. https://doi.org/10.3139/9783446471733.014

Einsatz von Holz bei der additiven Fertigung im Bauwesen

Use of Wood in Additive Manufacturing in Construction

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Kurzfassung

Die additive Fertigung im Bauwesen ist ein schnell wachsender Bereich der Forschung und Entwicklung an der Schwelle zur praktischen Anwendung. Zahlreiche Lösungen mit einer Vielzahl von Materialien in verschiedenen Prozessen wurden bereits vorgeschlagen. Doch obwohl die Verwendung von Holz in solchen Prozessen die Chance eröffnet, einen nachwachsenden Rohstoff einzusetzen und die Materialkosten zu senken, sind Beispiele für diesen Ansatz rar. In diesem Beitrag werden die grundsätzlichen Möglichkeiten des Einsatzes von Holz in der additiven Fertigung skizziert und einzelne Prozesse, die in Hinblick auf den großen Maßstab und auf eine Anwendung im Bauwesen entwickelt wurden, vorgestellt.

Short Abstract

Additive manufacturing in construction is a rapidly growing field of research and development on the threshold to practical application. Numerous solutions involving a large range of materials in various processes have already been proposed. However, even though the use of wood in such processes would open up the chance to employ a renewable raw material and to reduce material costs, examples of this approach are scarce. In this paper the general possibilities to use wood in additive manufacturing are outlined and single processes, devised with a focus on the large scale and applications in construction, are presented.

1 Introduction

1.1 Additive manufacturing in construction

In additive manufacturing (AM) parts are generated by joining units of feedstock material on the basis of a digital 3D model. Therefore, no specialized tools are necessary to fabricate differently shaped objects. This makes additive manufacturing particularly economical where single items or small batches are to be produced. Furthermore, AM allows a high degree of geometric freedom and offers the opportunity to form parts that otherwise can only be produced with great effort.

Building, whether traditional or industrial, has always been characterized by single-item production, often involving high geometric complexity. For this reason, AM and construction are a perfect match. In addition, additive manufacturing in construction (AMC) allows the optimization of building components regarding, for example, their structural, thermal or acoustic performance. Also, additional functions such as ducts for installations can be integrated without the need for further work steps.

However, the transfer of AM into construction is not trivial. At least two challenges have to be met: firstly, the extensive scale of the specific structures in architecture and civil engineering, and secondly, the high and diverse demands (e.g. weather-protection, loadbearing, durability) on construction materials. Consequently, large scale AM processes with materials which are suited for applications in construction have to be developed.

First proposals for AMC processes, both for concrete, were published in 1995 by J. Pegna [1] and 1999 by B. Khoshnevis [2]. Since then this technology has gained substantial momentum. Today a large number of activities related to AMC, including a growing collection of real scale demonstrators, can be observed worldwide. In these projects different combinations of materials (clay, metal, plastics) and processes (material extrusion, binder jetting) are being explored, with concrete still being the most favored material [3]. Examples for the use of wood in AMC, however, are scarce.

1.2 Additive manufacturing by the use of wood

The use of wood in AM opens up the chance to employ a renewable raw material in this rapidly developing manufacturing technology. Furthermore, next to the ecological significance, it may help enhance material properties and reduce material costs. For these reasons, using wood in AM has gained high attention in recent years.

There are three fundamentally different approaches to additive manufacturing with wood which can be differentiated by the degree of destruction of the native wood. The least intervention into the original structure of the naturally grown wood takes place in such approaches where the fabrication of the objects is executed by assembling discrete elements from solid wood. The highest degree of disintegration occurs in such processes where the wood is dissolved into its basic chemical substances for the formulation of bio based polymers [4, 5]. Between those two extremes lies the third approach where wood particles are used in the feedstock for the additive manufacturing processes.

It has been proven that the fabrication of large structures by computerized assembly of discrete timber elements is feasible [6, 7]. However, as this approach requires the controlled handling of the distinguishable, individual elements, it does not represent AM in a narrow sense and will not be covered in this review. Nevertheless, an exception is made for sheet lamination (see paragraph 2.5) where the feedstock is solid sheet material and which is usually considered to be an AM-process [8, 9]. All other investigations on large scale AM by the use of wood deal with particle-based processes.

Additive manufacturing by the use of wooden particles can be accomplished in many different ways. This includes deposition processes, where solids are built up by depositing material (e.g. material extrusion), as well as selective solidification processes, where solids are generated by selectively solidifying parts of a larger volume of formable material (e.g. powder bed fusion or binder jetting).

In all these cases the wood-based bulk is incorporated into the AM-process by combining it with some kind of binder as a matrix. This matrix may be a thermoplastic material, thus making the resulting wood composite processible in such processes of material extrusion, where objects are generated by depositing molten material [10], or in powder bed fusion, where this is accomplished by selectively fusing areas of a particle bed by a laser [11]. Alternatively, the matrix may be a binder with a physical or chemical hardening mechanism. Such composites can be processed via paste extrusion, where a paste is deposited commonly in strands [12], as well as by binder jetting, were particles are bound by intruding a fluid into bulk material [13].

While most of the research on additive manufacturing by the use of wood is limited to small scale, there are only a few attempts to transfer this technology into the large scale needed for applications in construction.

2 Wood-AM for the large scale and applications in construction

2.1 Material extrusion - extrusion of molten thermoplastic material

In molten material extrusion a thermoplastic material is melted and then deposited commonly in thin strands. The use of wood can be realized by adding a wood-based filler to a thermoplastic matrix. The matrix itself may be bio-based as well, as in the case of the widely used polylactic acid (PLA). Material extrusion of molten wood plastic composites has been researched in a large number of projects [10] for a decade now [14]. Today there is feedstock commercially available on the market, either as pellets or as filament with up to 40 wt.% of wood-based filler [10]. Such filaments can be processed in standard desktop "3D printing" devices. In this context the process is commonly referred to as fused filament fabrication or fused deposition modelling.

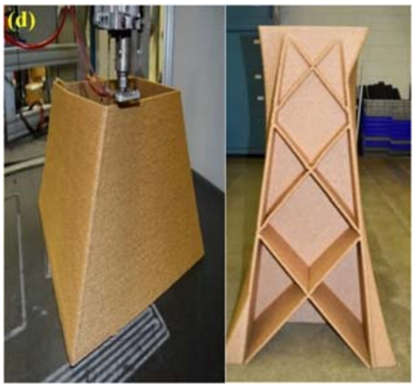

Figure 1. Podium base manufactured by molten material extrusion using pellets consisting of poplar fibers and PLA during (left) and after fabrication (right) [15].

Figure 2. Concrete formwork manufactured by molten material extrusion from UPM Formi 3D material, consisting of cellulose fibers and PLA [17].

The feasibility of the use of wood in large scale additive manufacturing by molten material extrusion has been demonstrated in a small number of projects. Wood-composites containing 20 wt.% poplar fibers and 80 wt.% of PLA proved suitable to fabricate large-scale objects by molten material extrusion [15]. The feedstock in form of pellets was processed in a Big Area Additive Manufacturing (BAAM) system, which has a build volume of (L x W x H) 6 m × 2.5 m × 1.8 m, at the Manufacturing Demonstration Facility (MDF) of Oak Ridge National Laboratory, Tennessee, USA. The nozzle that was put to use had an orifice diameter of 7.62 mm, while the layer height was set to 5.84 mm. With this setup a full-scale podium base, shown in Figure 1, was fabricated. In [16] the use of the BAAM-device for the fabrication of a large scale boat roof mold is reported with the feedstock being pellets made from 20 wt.% wood flour in a PLA matrix.

UPM Formi 3D is a commercially available fiber filled plastic composite. Principal ingredients are cellulose fibers and native PLA. Two material variants are available with a declared fiber content of 20 % (Formi 3D 20) and 40 % (Formi 3D 40) [18]. The different grades of Formi 3D are available as pellets. They are suited to be either used directly in granulate-based material extrusion or as feedstock for the production of filament. Several large scale objects additively manufactured with this material are documented on the producers web page (Figure 2) [17].

2.2 Material extrusion - extrusion of paste-like material

In this subcategory of material extrusion, objects are built by depositing a paste material, typically in form of strands. After deposition the paste hardens by a physical or chemical mechanism. In clay extrusion, for example, the material hardens by the physical mechanism of drying. Cement on the other hand, solidifies by the chemical process of hydration. The use of wood can be achieved by adding wooden particles to a paste-like matrix. Different matrices like adhesives [19], methylcellulose [12] and fast-setting mineral binders [20] have been investigated. Also starch matrices were examined to develop wood-starch-composites suitable as feedstock for support structures in concrete extrusion [21].

Figure 3. Additive manufacturing of wall elements by extrusion of wood concrete (picture K. Henke)

Research on large scale AM for a direct application in construction has been executed using wood chips in a cement paste matrix [22]. The main ingredients of this wood concrete were, next to water, Portland-limestone cement and untreated softwood chips in a ratio by volume of 1:1. Both components contribute to the functionality of the composite, designed for the application in construction. Load bearing capability and fire protection e.g., are provided by the matrix, while the wood particles add further properties such as thermal insulation and fiber reinforcement. Several large-scale demonstrators were manufactured with this material using a custom-made conveyor screw extruder with a nozzle opening diameter of 20 mm. A 6-axis industrial robot was used as a manipulator. The layer height was set to 10 mm. The largest of those objects was a wall structure measuring (L x W x H) 1,500 mm x 500 mm x 930 mm (Figure 3) [22].

2.3 Binder jetting

In binder jetting a fluid is applied locally to a volume of bulk material, to selectively bind the particles in those areas where the desired part is intended to be generated. The fluid can be a liquid binder. Alternatively, a dry component of the binder system can be added to the bulk as powder, which is then activated by the application of a fluid. In both cases these processes operate layer by layer. After finishing the last layer the unbound material is removed. Binder jetting is characterized by a high geometric freedom, as the unbound material acts as a support for overhanging or bridging regions of the parts. The process was developed as three-dimensional printing with the distinct goal of being able to use a wider variety of materials [23].

Figure 4. Tube with inner struts fabricated by selective binding of wood chips with cement (picture R. Rosin, HFM)

Wood can be processed in binder jetting in combination with different binders [13]. Tests were performed with wooden chips made of spruce as bulk material and cellulose, gypsum and cement as binder. Testing devices consisted primarily of a build space with a vertically movable work platform, which is lowered stepwise according to the intended layer thickness. The chips were first mixed with the dry binder. After creating a thin layer in the build space by scattering the dry mixture, water was then applied with spray valves to activate the binding process. The locally limited application of the water was realized by the use of masks. Different ratios (by weight) of chips to binder and water to binder were tested. The best results were gained using cement with a chips/cement ratio of 0.15 and a water/cement ratio of 0.80 [13]. Figure 4 shows an object fabricated in this way from wood chips and cement [24]. It measures (L x W x H) 200 mm x 200 mm x 200 mm. The layer height was set to 2.0 mm.

2.4 Individual layer fabrication

Individual layer fabrication (ILF) has been devised explicitly for the manufacturing of large-scale wooden structures. In individual layer fabrication objects are built up by laminating individually contoured panels, but contrary to sheet lamination (see paragraph 2.5), the panels are not fabricated subtractively by cutting sheet material but additively by selective binding of wood particles. As each layer is fabricated individually, the process allows the application of mechanical pressure. Thereby, compared to other additive manufacturing techniques, the necessary amount of binder can be significantly reduced and mechanical properties comparable to particle boards can be achieved.

Figure 5. Individual layer fabrication: application of adhesive onto the layer of scattered wood chips (left) and individually contoured panel after pressing (right) (picture left D. Talke, right M. Anzinger)

The ILF-process is still under development. In a feasibility study it was shown that individually contoured panels could be fabricated by selective binding of wood chips (spruce, particle size 0.8 - 1.1 mm). After locally applying the adhesive (polyvinyl acetate) to the layer of bulk by the use of a progressive cavity pump and a CNC-portal (Figure 5, left), the layer was pressed. After removing the unbound particles, the contoured panel (layer thickness 2 mm) could be retrieved (Figure 5, right). By laminating a series of such individually contoured panels solid objects can be fabricated [25].

2.5 Sheet lamination

In sheet lamination objects are built up by sequentially laminating contoured panels of sheet material. The contouring of the panels is realized by computer guided cutting of the sheet material, e.g. by a laser beam. With this method, materials such as paper, plastics, metal and others can be processed [26].

The use of wood in sheet lamination was already addressed in the patent "Laminated object manufacturing apparatus and method" filed 1995 by Helisys, Inc. [27]. In this case the feedstock may be veneer or plywood, where the degree of destruction of the naturally grown wood is comparatively low. That way, much of the original properties of the solid wood can be preserved. On the other hand, sheet lamination is always also characterized by the production of considerable amounts of waste, and the subtractively removed material cannot be directly returned to the process.

Figure 6. Real scale reconstruction of a baroque church, constructed by stacking CNC-cut layers of solid fir wood boards [28]

Figure 6 shows the real scale reconstruction of Borrominis church San Carlo alle Quattro Fontane (Rome, Italy) at Lago Lugano (Lugano, Switzerland). It was erected for an exhibition in 1999 by stacking CNC-cut layers of solid fir wood boards of 45 mm thickness, held together by steel cables [28]. Not quite the result of a fully digital fabrication process it is still a good illustration of the potential of constructing large scale structures by stacking contoured layers of wood.

3 Summary

The use of wood in additive manufacturing can be realized by a large number of different processes with quite diverse characteristics. Some of these solutions have the potential to be put to use in large-scale additive manufacturing for applications in construction.

In material extrusion and binder jetting, the matrix provides the predominant part of the composite with the effect that the properties of the composite are determined to a great extent by the properties of the matrix material. Those approaches will only be able to meet the extensive requirements of the application if the matrix material itself is able to do so.

In sheet lamination, on the other hand, the wood content can be significantly higher, so that more of the properties of the native wood are transferred into the additively manufactured parts. This exactly is also the goal of individual layer fabrication. The strategy here, in further developing this process, will be to reduce the amount of binder to an extent that it matches other wood products already in use and approved in the construction industry.

4 Acknowledgements

The research on extrusion of wood chip concrete was conducted within the project 'Additive Manufacturing of Freeform Building Elements by Numerical Controlled Extrusion of Wood Chip Concrete'. It was funded by the innovation program 'Zukunft Bau' of the Federal Ministry of the Interior, Building and Community, Federal Republic of Germany (project number SWD-10.08.18.7-14.10).

The research on selective binding of wood based bulk material was executed in collaboration with Wood Research Munich of the Technical University of Munich.

The research on Individual Layer Fabrication is being conducted within the project 'Structural Timber by Individual Layer Fabrication (ILF)'. The project is part of the collaborative research center 'Additive Manufacturing in Construction - The Challenge of Large Scale', funded by the Deutsche Forschungsgemeinschaft (DFG, German Research Foundation) - project number 414265976 - TRR 277.

The objects shown in Figure 4 and Figure 5 are the result of student work at the chair of the authors. The object shown in Figure 4 was fabricated by Sonja Medele, the work shown in Figure 5 was executed by Marlene Anzinger.

5 References

[1] J. Pegna, "Applications of Cementitious Bulk Materials to Site Processed Solid Freeform Construction," in *Proceedings of the 6th Solid Freeform Fabrication (SFF) Symposium, 1995, Austin, Texas*.

[2] B. Khoshnevis, "Contour Crafting - State of Development," in *Proceedings of the 10th Solid Freeform Fabrication (SFF) Symposium, 1999, Austin, Texas*.

[3] Y. W. D. Tay, B. Panda, S. C. Paul, N. A. Noor Mohamed, M. J. Tan, and K. F. Leong, "3D printing trends in building and construction industry: a review," *Virtual and Physical Prototyping*, vol. 12, no. 3, pp. 261–276, 2017, doi: 10.1080/17452759.2017.1326724.

[4] R. A. Pradhan, S. S. Rahman, A. Qureshi, and A. Ullah, "Biopolymers: opportunities and challenges for 3D printing," in *Biopolymers and their Industrial Application: From Plant, Animal, and Marine Sources, to Functional Products*: Elsevier, 2020, pp. 281–303.

[5] J. Liu, L. Sun, W. Xu, Q. Wang, S. Yu, and J. Sun, “Current advances and future perspectives of 3D printing natural-derived biopolymers,” *Carbohydrate polymers*, vol. 207, pp. 297–316, 2019, doi: 10.1016/j.carbpol.2018.11.077.

[6] P. Eversmann, F. Gramazio, and M. Kohler, “Robotic prefabrication of timber structures: towards automated large-scale spatial assembly,” *Constr Robot*, vol. 1, 1-4, pp. 49–60, 2017, doi: 10.1007/s41693-017-0006-2.

[7] H. Yoshida *et al.,* “Architecture-scale human-assisted additive manufacturing,” *ACM Trans. Graph.*, vol. 34, no. 4, pp. 1–8, 2015, doi: 10.1145/2766951.

[8] T. Wohlers and T. Gornet, “History of additive manufacturing,” in *Wohlers Report 2016*.

[9] *ISO / ASTM DIS 52900-18, Standard Terminology for Additive Manufacturing – General Principles – Fundamentals and vocabulary, West Conshohocken, PA.*

[10] M. E. Lamm *et al.,* “Material Extrusion Additive Manufacturing of Wood and Lignocellulosic Filled Composites,” *Polymers*, vol. 12, no. 9, 2020, doi: 10.3390/polym12092115.

[11] K. Y. Jiang, Y. L. Guo, W. L. Zeng, and Z. S. Xin, “The Preparation of WPC for SLS Rapid Prototyping and Manufacturing,” *AMR*, 113-116, pp. 1722–1725, 2010, doi: 10.4028/www.scientific.net/AMR.113-116.1722.

[12] M. Rosenthal, C. Henneberger, A. Gutkes, and C.-T. Bues, “Liquid Deposition Modeling: a promising approach for 3D printing of wood,” *Eur. J. Wood Prod.*, vol. 76, no. 2, pp. 797–799, 2018, doi: 10.1007/s00107-017-1274-8.

[13] K. Henke and S. Treml, “Wood based bulk material in 3D printing processes for applications in construction,” *Eur. J. Wood Prod.*, vol. 71, no. 1, pp. 139–141, 2013, doi: 10.1007/s00107-012-0658-z.

[14] K. Luo, H. Zhao, Y. Guo, and Z. Yuan, “„Principle of FDM Rapid Prototyping of PE/Wood Flour Composites,“,” *Journal of Northern Forestry University*, vol. 38, no. 10, pp. 126–128, 2010.

[15] X. Zhao *et al.,* “Poplar as Biofiber Reinforcement in Composites for Large-Scale 3D Printing,” *ACS Appl. Bio Mater.*, vol. 2, no. 10, pp. 4557–4570, 2019, doi: 10.1021/acsabm.9b00675.

[16] D. J. Gardner, J. Anderson, H. L. Tekinalp, S. Ozcan, and P. Sauerbier, “Lignocellulosic-filled polymer feedstocks for large scale additive manufacturing of low cost composites,” in *Proceedings of the Internaional Forest Products Congress, Trabzon, Turkey, 2018*, pp. 12–22.

[17] UPM Biocomposites, *UPM Formi.* [Online]. Available: https://www.upmformi.com/biocomposite-products/3d-printing/large-scale-additive-manufacturing/ (accessed: Dec. 14 2020).

[18] UPM Biocomposites, *Technical Specification UPM Formi 3D.* [Online]. Available: https://www.upmformi.com/siteassets/documents/formi-3d/upm-formi-3d-product-data-sheet-en.pdf (accessed: Dec. 14 2020).

[19] M. Kariž, M. Sernek, and M. K. Kuzman, “Use of wood powder and adhesive as a mixture for 3D printing,” *Eur. J. Wood Prod.*, vol. 74, no. 1, pp. 123–126, 2016, doi: 10.1007/s00107-015-0987-9.

[20] M. Sinka, J. Zorica, D. Bajare, G. Sahmenko, and A. Korjakins, “Fast Setting Binders for Application in 3D Printing of Bio-Based Building Materials,” *Sustainability*, vol. 12, no. 21, p. 8838, 2020, doi: 10.3390/su12218838.

[21] J. Kaufhold et al., “Wood-based support material for extrusion-based digital construction,” Rapid Prototyping Journal, vol. 25, no. 4, pp. 690–698, 2019, doi: 10.1108/RPJ-04-2018-0109.

[22] K. Henke, D. Talke, and S. Winter, “Additive Manufacturing of Building Elements by Extrusion of Wood Concrete,” in *World Conference on Timber Engineering WCTE 2016*.

[23] E. M. Sachs, J. S. Haggerty, M. J. Cima, and P. A. Williams, “Three-dimensional printing techniques,” US 5340656A, Aug 23, 1994.

[24] K. Henke, D. Talke, and S. Winter, “Multifunctional Concrete - Additive Manufacturing by the Use of Lightweight Concrete,” in *Proceedings of the IASS Annual Symposium 2017*, A. Bögle and M. Grohmann, Eds., Hamburg, 2017.

[25] K. Henke, D. Talke, F. Bunzel, B. Buschmann, and C. Asshoff, “Individual Layer Fabrication (ILF) - A Novel Approach to Additive Manufacturing by the Use of Wood,” *Eur. J. Wood Prod.*, 2021, doi: 10.1007/s00107-020-01646-2.

[26] M. Feygin and B. Hsieh, “Laminated Object Manufacturing (LOM): A Simpler Process,” in *1991 International Solid Freeform Fabrication Symposium*, 1991.

[27] M. Feygin and S. S. Pak, “Laminated Object Manufacturing Aparatus and Method,” US 5876550, May 2, 1999.

[28] A. Isopp, “Barocke Schichten - Borromini in Holz,” *Zuschnitt*, no. 44, p. 8, 2011.