3D PRINTING – A REVIEW OF TECHNOLOGIES, MARKETS, AND OPPORTUNITIES FOR THE FOREST INDUSTRY

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ABSTRACT

3D printing has been used to produce prototypes and molds in industry for many years. It is now gaining increasing interest, due to its expansion into consumer products markets as well as the exploration of potential applications in manufacturing large architectural structures. Recent intellectual property changes (especially the expiration of early patents) have led to the availability of low-cost 3D printers and novel applications of 3D printing technology. This has turned 3D printing from a small-scale prototyping tool into a potential game changer for product development and manufacturing. This report summarizes the development of 3D printing, its markets, and its applications in the short and medium term. 3D printing is ideal for mass customization, but is not yet capable of mass production because of limitations on cost, speed, and materials. The near future of 3D printing will focus on production tooling, on-demand parts at low volumes, design and educational tools, products made at home, and even large architectural structures.

The potential applications for forest products have been examined. Forest industry products based on wood fibres and wood-based biomaterials are already being prototyped using 3D printing. There is also increasing interest in using wood-based materials as feedstocks for 3D printing to impart a unique appearance to printed products and meet the demand for sustainability from consumers. This development could become part of transforming the forest industry from production of commodities to production of high-value-added specialty products. Some opportunities for the forest industry have been identified.

INTRODUCTION

Only five years ago, 3D (three-dimensional) printing technology was rarely seen outside of trade shows and development centres, producing prototypes and structures that could not be produced by conventional manufacturing. Since then, 3D printing has started to expand very rapidly. Home hobbyists can now buy 3D printers at low cost. The aerospace, automotive, and military industries are investing heavily in the field with the stated goal of fabricating high-quality objects in low to medium volumes using 3D printing [1]. The news media—both technical and popular—now carry articles and features on 3D printing on a regular basis.

STATUS OF TECHNOLOGY DEVELOPMENT

Types, Technologies, and Materials that can be Handled

Many processes and materials are defined as 3D printing. Based on ISO/ASTM 52921:2013 E, Terminology for Additive Manufacturing, 3D printing technologies can be categorized as in Table 1.

Material Extrusion

Fused deposition modelling (FDM) (Fig. 1) systems represent the largest installed base of 3D printers [11]. In FDM, the printing nozzles (extrusion heads) melt and fuse thermoplastic material. The liquefied material is deposited layer by layer, directed by a digital file, to form the final

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TABLE 1 *Summary of key technologies.*

Type	Technologies	Materials (feedstocks)	Pros	Cons	Makers
Material extrusion	Fused deposition modelling (FDM) [2]	Thermoplastics (e.g., PLA, ABS)*, liquid metals, edible materials	Ideal for conceptual and engineering models and functional prototypes	Low resolution and high surface roughness	3DSystems (USA) Stratasys (Israel)
	Bio-printing [3]	Aqueous slurries and dispersions	Ideal for biomaterials	Maintaining structural integrity during drying	EnvisionTEC
Vat photo-polymerization	Stereo-lithography (SLA) [4]	Photopolymer	Excellent for high-resolution applications with complex geometries	Low speed, limited choice of photo-polymers	3DSystems Stratasys EnvisionTEC (Germany)
Material jetting	PolyJetTM [5]				
Granular material binding	Powder-bed fusion (e.g., SLS [6], SHS [7]) **	Thermoplastics, metal powders, ceramic powders	Ideal for durable, functional parts with a variety of applications	Low speed	- 3D Systems - Voxeljet (Germany) - SLM Solutions (Germany) - ExOne (USA) - EOS (Germany) - Arcam (Sweden)
	Binder jetting (3DPTM) [8]	Thermoplastics, plaster			
	Direct energy deposition [9]	Metal powders			
Sheet lamination	Laminated object manufacturing (LOM) [10]	Paper, metal foil, plastic film	Easy access to printing materials, wood-like 3D	Low strength, narrow application	Mcor (Ireland)

*polylactic acid (PLA), acrylonitrile butadiene styrene copolymer (ABS)
**selective laser sintering (SLS), selective heat sintering (SHS)

solid object. Since 2009, the number of low-cost 3D printers from both major and start-up companies has greatly increased, with many using the now off-patent FDM technology.

Bio-Printing

Bio-printing is another form of 3D printing that is particularly suited to biological materials. Bio-printers [3,12] may be constructed in a configuration similar to FDM printers, but the print heads deal with lower-viscosity feedstocks rather than hot-melt plastics. Because the feedstocks for bio-printing are aqueous slurries, a large volume of water may have to be removed. Bio-printing allows constructing a 3D "scaffolding", onto which the biomaterial is then printed. The application of this and similar devices to printing of biomaterials, including cellulosics, will be discussed below.

Vat Photopolymerization

In stereolithography (SLA) [4], the first patented and commercialized 3D printing process, a platform which serves as the base for the object is submerged into a vat of polymer. A UV laser cures and hardens these polymers with each pass over the object. Once a pass is finished, the platform lowers slightly into the vat, allowing more uncured polymer to cover the object.

Material Jetting

PolyJet 3D printers jet layers of liquid photopolymer onto a building tray and cure them with UV radiation [5]. The layers build up one at a time to create a 3D object. The PolyJet 3D printing technology possesses the advantage of higher printing resolution (layer height

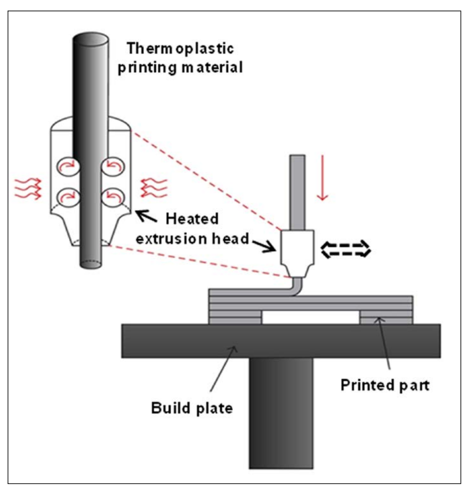

Fig. 1 - **Fused deposition modelling (FDM) [2].**

of 0.089–0.12 mm for PolyJet, compared to 0.1–0.3 mm for FDM) [5].

Granular Material Binding

The powder-bed fusion, binder jetting, and directed energy deposition technologies share the similarity of binding granules into solid objects. Granular material binding technologies have fewer feedstock constraints. One layer of a powdered raw material is added by an applicator that passes over the building plate. The materials are dried or hardened by laser, electron beam, or heat. The applicator makes another pass, and the next layer is added. As will be discussed below, this technology may be of critical interest to the forest products industry if the hardening agent is a printed adhesive. One form of granular material binding is shown in Fig. 2. Similarly to fused deposition printing, as the early patents for this process expire, a new series of low-cost printers may proliferate.

Current Market and Applications for 3D Printing

3D printing can facilitate understanding between designers and engineers as they bring design into reality. With a physical prototype, engineers can see the concept better in real terms (Fig. 3a). 3D printing also benefits the fashion and art design industries.

3D printing is starting to provide major benefits to medical device manufacturers to provide customization to patients at low cost, to satisfy the need to introduce innovative products, and to advance bioengineering (cell culturing). The feedstocks are mainly polymers, ceramics, metals, and biological cells. The value of 3D-printed medical products is predicted to grow from $11 million in 2012 to $1.9 billion in 2025 [13].

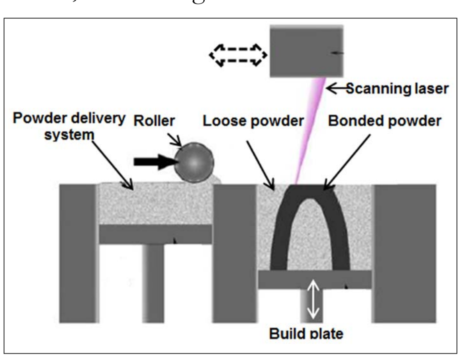

Fig. 2 - Powder-bed fusion [6].

With increased printing speed and material choices, 3D printing can open up more applications for direct part production. Hewlett-Packard, a leader in laser and ink-jet printing, has announced that they are developing their own proprietary "Multi-Jet Fusion" 3D printing technology. According to their most recent press releases, this technology will be officially introduced in 2016 [14]. They claim that this technology will be both faster and cheaper than those currently used.

Metal powder printing (followed by near-instantaneous high-temperature sintering and fusion) is growing rapidly. General Electric's Additive Development Center (part of its aviation division) produced a working model (approximately 30 cm in length) of a jet engine fabricated by 3D printing. Of greater importance, GE obtained approval for the commercial introduction of a jet engine nozzle manufactured by 3D printing. According to a news release, they expect more than 100,000 3D printed engine parts to be on the market by 2020 [15]. In a related application, a proposal has been made to 3D-print a metal bridge across a canal in Amsterdam [16].

3D printing technology also shows potential for fabricating large architectural structures. Contour Crafting [17] is a fabrication process by which large-scale parts can be fabricated quickly in a layer-by-layer fashion. Attempts are being made to use fibres to develop printable composite building materials. A private firm in China recently used a 10 m × 6.6 m printer to spray a mixture of cement and construction waste to fabricate sections of buildings layer by layer (Fig. 3b). Ten full-sized, detached single-story houses were made in one day [18]. A group at the Université de Nantes in France has proposed 3D printing of emergency shelters. The prototype—see the video link in the attached reference—was built out of a polyurethane material, but clearly there is room for other liquid/gel systems that are capable of being extruded [19].

3D printing may even be used in space. NASA is supporting a revolutionary suite of technologies called "SpiderFab" [20] to enable efficient fabrication in orbit of spacecraft and space-station components that are too large to be transported in current launch vehicles, such as antennas, solar panels, trusses, and other multifunctional structures (Fig. 3c).

Any material that can be passed through an extruding nozzle can be printed, including food products and pastes. NASA awarded $125,000 to Systems and Materials Research Consultancy (SMRC) to study how to "print" food during long space missions. The project made headlines largely because of the first item on the menu: a 3D-printed space pizza. Cellulose-based food additives could be included in the recipe for printing ingredients [21].

Main Feedstocks and Requirements

Feedstocks for 3D printing can be categorized into thermoplastics, photopolymers, metal powders (stainless steel, sterling silver), and other powders (glass, ceramics, resin, sandstone, rubber, etc.; Fig. 4). The global materials market in 2013 in total was about 2,000 tons, which is equivalent to $450 million. The materials value

Fig. 3 - Representative objects produced by 3D printers: (a) printed architectural design model; (b) printed house; (c) concept for printed spacecraft component [22].

should exceed $600 million (about 9,700 tons) by 2025 in a development combining increased demand with reduced prices [23,24]. Thermoplastic filaments (Table 2) for FDM 3D printing accounted for 40% of the total feedstock market in 2013.

Filament materials for FDM printers that meet customers' needs for speed, strength, accuracy, surface resolution, chemical and heat resistance, colour, and mechanical properties must continue to be developed. Achieving the desired mechanical, thermal, and chemical resistance properties in a 3D-printed object involves a complex interplay between feedstock material properties and process parameters. Aside from the material properties, filament geometry also plays an important role in 3D printability and quality of the printed objects. Inconsistent filament diameter can lead to extruder failure and inconsistent extruded volume.

TABLE 2 *Thermoplastic feedstocks for FDM 3D printers.*

	ABS	PLA	PVA (PVOH) *
Produced from	Petroleum	Plant starch	Petroleum
Properties	Durable, strong, slightly flexible, heat-resistant	Tough, strong	Water-soluble, excellent film formation, good barrier properties
Extruder temp.	210°C–250°C	160°C–220°C	190°C–210°C
Pros	Great plastic properties, solidifies quickly, durable and difficult to break	Bioplastic and non-toxic	Biodegradable, recyclable, non-toxic
Cons	Petroleum-based, deteriorates in sunlight	Slow cooling, low heat resistance, easier to break than ABS	Expensive, deteriorates with moisture, special storage necessary

*Polyvinyl alcohol

Challenges in Moving 3D Printing to Manufacturing

Significant technological and business hurdles must be overcome before 3D printing can live up to its most ambitious promises. 3D printing in its current state is very good at recreating geometric and organic complexity. However, 3D printed objects are usually not as durable as traditionally manufactured products. Although a printed wrench is functional, it will not last as long as one produced through drop forging of high-strength steel. Therefore, to reach the point where the average consumer can print "ready-to-go" objects from a home printer, durability must be improved. Another technical challenge for printed objects is the "as printed" look and feel. Almost all 3D printing technologies to date require some level of post-processing (e.g., deburring, sanding, priming, and, airbrushing), although many expect a 3D printed part to look completely smooth and finished when it is done printing. Besides the properties of the printed objects, printing speed is also a hurdle for moving 3D printing to mass manufacturing. Although ideal for mass customization, the technology is not yet capable of mass production. The practical usefulness of 3D printing for a manufacturer is to fabricate 100 airplane parts rather than one million smartphone cases.

A new product manufacturing concept, community-driven manufacturing, is currently emerging. For example, Shapeways is an on-line service platform that enables users to design and upload 3D printable files. The objects are then printed and shipped by Shapeways [25]. 3D Hubs is another on-line 3D printing service that operates a network of 3D printers with over 15,000 locations in 140 countries [26].

FOREST PRODUCTS 3D PRINTING AND BIOPRINTING

Considerable research is ongoing to use wood and forest products as 3D printing feedstocks. These efforts span the range from large-scale building manufacturing to small-scale, highly specialized value-added bio-printing. Through market analysis and technology assessment, FPInnovations is creating a vision of how the forest industry can use 3D printing technologies (Fig. 5).

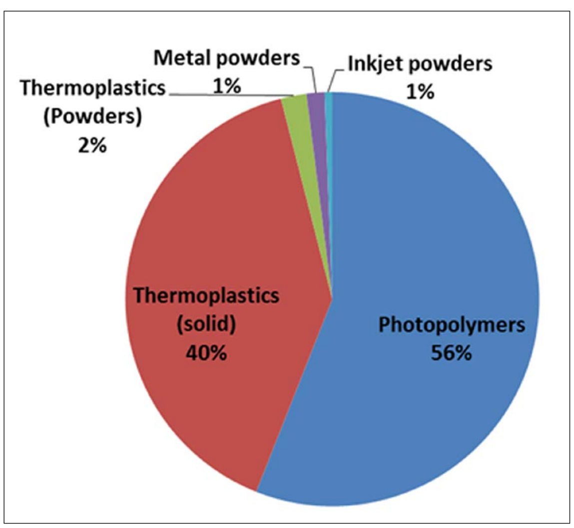

Fig. 4 - Breakdown of the printing materials market in 2013 (total ~2000 tons) [23].

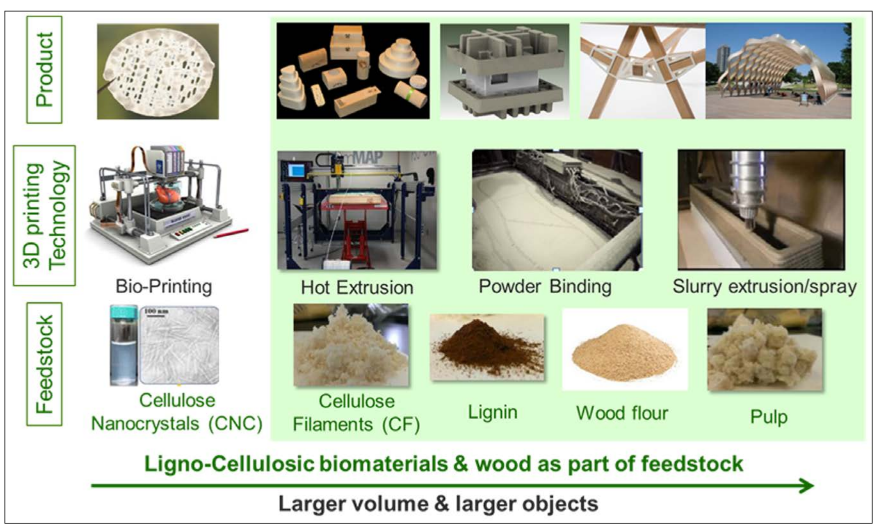

Fig. 5 - FPInnovations' vision of 3D printing for the forest industry.

Niche Markets for Speciality Wood Products

Use of lignocellulosic materials as fillers in powder and fused-deposition printing - 3D printing of thermoplastic filaments has grown considerably in recent years, and there is already a demand for "green" substitutes for petroleum-based thermoplastics. Polylactic acid (PLA) is currently the principal biomaterial for fused-deposition 3D printing, but has issues of low strength, low flexibility, poor thermal stability, and poor 3D printability. Biomaterials extracted from forest products can be tuned to address these issues (Table 3). However, their market potential and value remain to be established.

TABLE 3 *Potential improvement for filaments with biomaterials.*

Problem with existing filaments	Potential solution	What we know
Strength, hardness, flexibility, heat resistance	CNC[(1)], CF[(2)], NFC[(3)], and MFC[(4)] as reinforcing agents	CNC reinforces PLA films [27,28] CNC is compatible with PVA [29,30]
Premature oxidation	Use lignin fillers in 3D printing	Lignin is a known anti-oxidant (free radical scavenger) [31,32]
Flammable		Lignin is a fire retardant [33]
Moisture-sensitive	Functional derivatives of CNC, CF, NFC, and MFC to give water resistance	The surfaces of CNC, CF, NFC, and MFC can be chemically modified [34,35]
Many synthetic polymers are not compostable	Biopolymers are compostable	N/A

(1) Cellulose nanocrystals
(2) Cellulose filaments
(3) Nanofibrillated cellulose
(4) Microfibrillated cellulose

Significant efforts world-wide in recent years have led to the production of large quantities of biomaterials in pilot and demonstration plants. However, technical challenges exist in developing feedstock formulations that will match wood fibres, cellulosic biomaterials, or lignin with the most appropriate 3D technology. Work at FPInnovations and elsewhere has shown that these problems can be solved, at least at the scale of proof-of-principle.

FPInnovations and Emily Carr University of Art and Design (Vancouver) collaborated to explore 3D printing of powdered lignin using powder-binding technology. The objects in Fig. 6(a) are composed of lignin plus binder. This work is being continued by FPInnovations and includes the development of wood-based filaments for 3D FDM technology. The objects shown in Fig. 6(b) are made from filaments composed of thermoplastic polymers containing lignin filler and fibre materials.

Wood-containing thermoplastic filaments supplied by non-systems manufacturers for fused-deposition printing are already on the market. In 2012, CC-Products created Laywoo-D3 [36], which contains up to 40% recycled wood fibre combined with a thermoplastic polymer binder (Fig. 7a). ColorFabb, produced by Helian Polymers of The Netherlands, offers Woodfill™, which contains 25%–30% milled wood fibre in a thermoplastic resin (Fig. 7b) [37].

Use of cellulosic materials in bioproducts - As already noted, 3D printing is being actively developed by medical device manufacturers. In one recent life-saving case, a bronchial "splint" was 3D-printed to help expand the bronchial tubes of an infant. The device was made from a biopolymer (polycaprolactone) and is expected to be gradually absorbed into the child's body, allowing its own pulmonary system to take over [38]. The ease with which cellulosic derivatives form stable dispersions and gels in aqueous media provides an excellent opportunity for new bioproducts. Although removing large amounts of water presents an obvious drawback, this remains an active area of world-wide research.

Using a bio-printer, Swansea University in Wales has prepared 3D-printed wound dressings (Fig. 8a) using nanofibrillated cellulose (NFC) supplied by the Norwegian Paper and Fibre Research Institute (PFI) [39]. They described their resulting material as strong, able to be kept under moist conditions, and possessing inherent anti-microbial activity—this last perhaps the result of surface modification during the oxidative process used to prepare the nanofibrils. The Swansea group also used more conventional materials to build a 3D scaffolding that effectively formed a collagen-like structure [40], as shown in Fig. 8b.

A different approach was taken by a group in Sweden and involved a dissolving pulp (in an ionic solvent) as the cellulose source [41]. The printed cellulosic gel was then immediately coagulated by overprinting a layer of water. Successive layers could then be built up. Although the solvent used in that particular work is rather exotic, there exists a very extensive

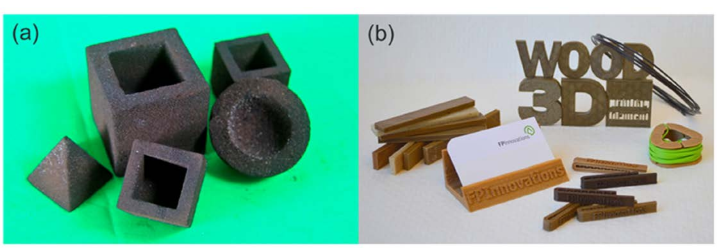

Fig. 6 - Developing lignocellulosic-based feedstock for 3D printing at FPInnovations: (a) prototypes made using the powder-binding technology; (b) prototypes made using FDM technology.

Fig. 7 - Application of wood fibre in 3D printing: (a) Laywoo-D3™ [36]; (b) WoodFill™ developed by ColorFabb [37].

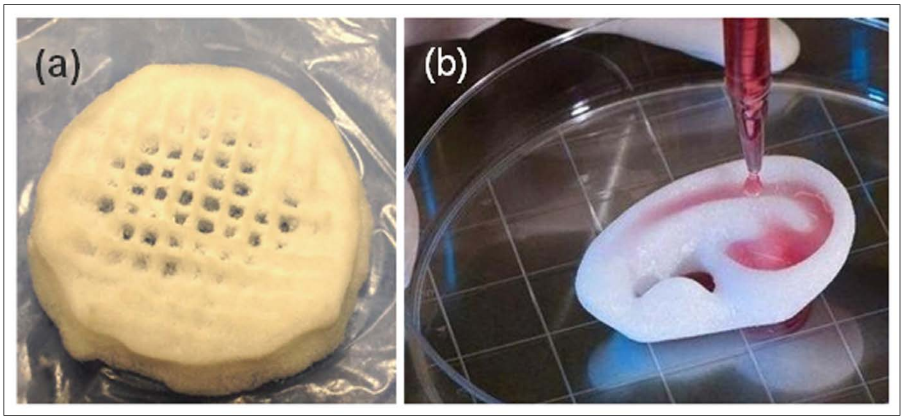

Fig. 8 - Bioplotted 3D structures: (a) wound dressing with inherent anti-microbial properties, printed from nanofibrillated cellulose (NFC); (b): printed model human ear made from a collagen-like material.

Fig. 9 - Truncated cone generated by 3D printing with spruce chips and gypsum, cut open to show the inner texture [39].

chemistry for dissolving and then regenerating cellulose, which could be applied.

Large-scale uses for commodity wood products - 3D printing of building components and even entire buildings has gained considerable attention around the world. So far, workers in the field tend to use concrete or related materials in extrusion-type printers [e.g., [17]]. At the same time, forest industry researchers are examining the potential for using wood products in large-scale 3D printed construction.

Several difficulties exist with any potential deposition system for slurries, especially with high water content or if fine detail is desired. A slurry:

1. Must have the appropriate rheology to flow out of the nozzle. This may become an issue with higher solids content.
2. Must be solid enough to support the next layer. In other words, it must dry quickly and not collapse. For some structures, forms may help.
3. Must bind well with the next layers printed.
4. Cannot solidify within the chamber or the nozzle.

Researchers at the University of Sydney (Australia) recently received funding to develop "micro timber" [42]. The process, which was not fully described, claims to use wood products as one element in 3D panel printing. Potential ingredients include hardwood and softwood fibres, wood flour, and even wood waste. Other details (including binders) have not yet been disclosed.

This work can be compared to concrete extrusion printing [e.g., [17]], in which either the concrete could contain wood fibres as a reinforcing component, or the main solid portion of the structure could be wood-based. Concrete as an aqueous slurry is also subject to the requirement that the structure rapidly become self-supporting—certainly before the next layer is printed.

The Oxman group of the MIT Media Lab is dedicated to both the art and science of 3D printing. In particular, they have a special interest in both permanent and biodegradable structures. A very recent publication on "water-based engineering" [43] described printing composites made from chitosan and cellulose, among many other materials.

Another variation on this theme is to use wood products (e.g., fibres, wood flour, or even wood chips) in a form of powder-bed printing. Just as in powder-bed printing with sand or any other material, the wood product would form the "powder bed", and complex structures would be built up by printing a suitable adhesive layer by layer. Researchers at the Technische Universität München demonstrated a truncated cone (Fig. 9) generated by 3D printing with wooden chips as the bulk material and gypsum, methyl cellulose, sodium silicate, and cement as the binder [44].

3D printing has also been proposed for manufacturing packaging and absorbent products by both Golden Hongye Paper and a research group at Shaanxi University of Science and Technology in China. Their concept is to print and form customized paper products with special functional requirements by alternatively depositing fibre layers and adhesive layers onto a build plate according to a digital model. This process is claimed to offer the potential benefits of reduced energy consumption, material waste, and pollution compared to traditional paper production and of a shorter production cycle [45].

SUMMARY AND IMPLICATIONS

In spite of the ongoing debate on whether 3D printing is a game-changer [46], applications of 3D printing are expanding beyond simple prototyping. Niche commercial applications can already be found in the medical, customized fashion, and high-tech industries. 3D printing is ideal for mass customization, but is not yet capable of mass production because of limitations on cost, speed, and materials. The near future of 3D printing will be focussed on production tooling, on-demand parts at low volume, design and educational tools, products made at home, and large, high-value architectural structures.

A growing interest in "green" feedstocks has created potential opportunities for wood fibres, other cellulosic materials, and biomaterials. Appearance, toughness, temperature and water resistance, durability, biocompatibility, and castability are among the key attributes of this feedstock. Forest materials with the desired characteristics (flexibility, strength, ease of chemical modification) could provide or enhance these desired feedstock functionalities. In addition to taking advantage of the increasing demand for feedstocks, the forest industry could also create new, high-value products for 3D manufacturing technology, starting with newly developed biomaterials such as CNC, CF, NFC, MFC, and lignin. In the longer term, 3D printing may have potential in producing sophisticated, high-performance absorbent and advanced packaging products.

REFERENCES

1. PriceWaterhouseCoopers LLP, "3D Printing: A Potential Game Changer for Aerospace and Defense", Available at: http://www.pwc.com/us/en/industrial-products/publications/gaining-altitude-with-pwc/issue-7-3d-printing.jhtml. 2013; retrieved May 2, 2014.
2. Tsouknidas, A., "Friction-Induced Wear of Rapid Prototyping-Generated Materials: A Review", Advances in Tribology, 2011.
3. EnvisionTEC, http://envisiontec.com/3d-printers/3d-bioplotter/. Retrieved August 12, 2015.
4. De Boer, J. "Shapeways and the Democratization of Production". Available at: http://fr.slideshare.net/jochem/shapeways-the-democratization-of-production-presentation. October 15, 2008; retrieved January 05, 2014.
5. http://www.engr.usask.ca/services/engineering-shops/facilities/rapid-prototyper.php#1, Retrieved January 25, 2014.
   http://www.sculpteo.com/en/3d-printing/3d-printing-and-traditional-manufacturing-processes/, Retrieved November 23, 2015.
6. Beaman, J.J. and Deckard, C.R., "Selective Laser Sintering with Assisted Powder Handling", U.S. Patent 4938816, assigned to the Board of Regents of the University of Texas, July 3, 1990.
   https://thre3d.com/how-it-works/powder-bed-fusion/selective-heat-sintering-shs, Retrieved January 25, 2014.
8. Sachs, E.M., Haggerty, J.S., Cima, M.J., and Williams, P.A., "Three-Dimensional Printing Techniques", U.S. Patent 5204055, assigned to Massachusetts Institute of Technology, 1993.
9. http://www.arcam.com/technology/electron-beam-melting/. Retrieved January 25, 2014.
10. http://www.mcortechnologies.com. Retrieved January 22, 2014.
11. Wohlers Associates, "3D Printing and Additive Manufacturing: State of the Industry", Wohlers Report, 2014.
12. EnvisionTEC, http://envisiontec.com/envisiontec/wp-content/uploads/MK-MPC-BioplotterPublishedPapers-V01-FN-EN.pdf. Retrieved August 12, 2015.
13. Lux Research, Inc., http://www2.luxresearchinc.com/component/content/article/164.html. Retrieved January 22, 2014.
14. Hewlett-Packard, http://www8.hp.com/us/en/commercial-printers/floater/3Dprinting.html, accessed August 5, 2015.
15. GE Reports, http://www.gereports.com/post/118394013625/these-engineers-3d-printed-a-mini-jet-engine-then; http://www.geglobalresearch.com/innovation/3d-printing-creates-new-parts-aircraft-engines. Retrieved August 5, 2015.
16. The Guardian, http://www.theguardian.com/technology/2015/jun/17/dutch-startup-plans-first-3d-printed-steel-bridge-to-span-amsterdam-canal, retrieved July 23, 2015.
17. http://craft.usc.edu/CC/modem.html, retrieved January 05, 2014.
18. http://www.bbc.com/news/blogs-news-from-elsewhere-27156775, retrieved April 23, 2014.
19. http://www.univ-nantes.fr/1435591545031/1/ficheactualite/&RH=INSTITUTIONNEL_FR, retrieved, August 14, 2015.
20. http://www.tethers.com/SpiderFab.html, retrieved January 05, 2014.
21. http://www.space.com/21308-3d-printing-nasa-space-food.html#sthash.lrROmBJw.dpuf, retrieved January 05, 2014.
22. http://www.stratasys.com/resources/case-studies/architecture/rietveld-architects; http://www.bbc.com/news/blogs-news-from-elsewhere-27156775; http://www.tethers.com/SpiderFab.html, retrieved August 12, 2015.
23. http://www.wired.com/design/2012/11/staples-goes-3-d, retrieved January 06, 2014.
24. Kneissl, W., 3D Printing Materials 2014-2025: Status, Opportunities, Market Forecasts. IDTechEX, 2013.
25. www.shapeways.com/.
26. https://www.3dhubs.com/.
27. Lin, N., Huang, J., Chang, P.R., Feng, J., Yu, J., "Surface Acetylation of Cellulose Nanocrystal and its Reinforcing Function in Poly (Lactic Acid)", Carbohydrate Polymers 83:1834 (2011).
28. Ramirez, M.A., Cellulose Nanocrystals-Reinforced Electrospun Poly (Lactic Acid) Fibers as Potential Scaffold for Bone Tissue Engineering, MSc thesis, North Carolina State University, 2010.
29. Peresin, M.S., Habibi, Y., Zoppe, J.O., Pawlak, J.J., Rojas, O.J., "Nanofiber Composites of Polyvinyl Alcohol and Cellulose Nanocrystals: Manufacture and Characterization", Biomacromolecules 11:674 (2010).
30. Zhang, W., He, X., Li, C., Zhang, X., Lu, C., Zhang, X., Deng, Y., "High-Performance Poly (Vinyl Alcohol)/Cellulose Nanocrystal Nanocomposites Manufactured by Injection Molding", Cellulose 21:485–494 (2014).
31. Pouteau, C., Dole, P., Cathala, B., Averous, L., Boquillon, N., "Antioxidant Properties of Lignin in Polypropylene", Polymer Degradation and Stability 81:9 (2003).
32. Dizhbite, T., Telysheva, G., Jurkjane, V., Viesturs, U., "Characterization of the Radical Scavenging Activity of Lignins—Natural Antioxidants", Bioresource Technology 95:309 (2004).
33. Chiricoa, A., Armaninia, M., Chinib, P., Cioccolob, G., Provasolia, F., and

Audisio, G., "Flame Retardants for Polypropylene Based on Lignin", Polymer Degradation and Stability 79(1): 139–145 (2003).

34. Stenstad, P., Andresen, M., Tanem, B.S., Stenius, P., "Chemical Surface Modifications of Microfibrillated Cellulose", Cellulose 15:35 (2008).

35. Habibi, Y., Lucia, L.A., Rojas, O.J., "Cellulose Nanocrystals: Chemistry, Self-Assembly, and Applications", Chemical Reviews 110:3479 (2010).

36. https://www.lulzbot.com/products/laywoo-d3-laywood-wood-filament-3mm, retrieved August 13, 2015.

37. http://www.3ders.org/articles/20131204-3ders-at-euro-mold-2013-digifabb-colorfabb.html, retrieved August 13, 2015.

38. http://www.scientificamerican.com/article/3-d-printed-windpipe/, retrieved August 14, 2015.

39. Gethin, D., Rees, A., Powell, L., Chinga-Carassco, G., Claypole, T., Deganello, D., Hill, K., Thomas, D., and Syverud, K., Studies on the 3D Printing of Nanocellulose Structures, Adv. Printing Sci. Technol. 41:91 (2014).

40. http://3dprint.com/62259/celleron-bioprinting/, retrieved August 14, 2015.

41. Markstedt, K., Sundberg, J., and Gatenholm, P., "3D Bioprinting of Cellulose Structures from an Ionic Liquid", 3D Printing and Additive Manufacturing.1:115 (2014).

42. http://sydney.edu.au/news/84.html?newsstoryid=15063. Retrieved August 14, 2015.

43. Soldevila, L.M. and Oxman, N., "Water-Based Engineering and Fabrication: Large-Scale Additive Manufacturing of Biomaterials", Materials Research Society (MRS 2015). Symposium NN Adaptive Architecture and Programmable Matter: Next Generation Building Skins and Systems from Nano to Macro (2015).

44. Henke, K. and Treml, S., "Wood-Based Bulk Material in 3D Printing Processes for Applications in Construction", Eur. J. Wood Prod. 71: 139–141 (2013).

45. Wang, Y. and Liang, J., CN 103061194, Paper Producing Method and Paper, 2012;
Zhu, J. and Liang, J., CN 102989032, Absorbing Core Body and Preparation Method Thereof as well as Absorbent Product Using Same, 2012;
Zhao, C., CN 104354297, Method for Producing Paper Package Box by 3D Printing Technology, 2014.

46. Uglow, B., Coe, N., Vig, R., Wood, A., and Davies, R., Capital Goods: 3D Printing, Mogan Stanley Blue Paper, September 2013;
Manyika, J., Chui, M., Bughin, J., Dobbs, R., Bisson, P., and Marrs, A., Disruptive Technologies: Advances that will Transform Life, Business, and the Global Economy, McKinsey Global Institute, May 2013;
Berman, B., "3-D Printing: The New Industrial Revolution", Business Horizons, 55