Call: HORIZON-WIDERA-2021-ACCESS-03/Twinning

Project SustDesignTex (GA No. 101079009), title: „Sustainable Industrial Design of Textile Structures for Composites" funded by the European Union

Deliverable Report

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Deliverable Title	**D.2.1.** ***(The Methodical Recommendations on rapid prototyping methods for business and science community)***
Deliverable Lead:	*University of Borås (HB)*
Related Work Package:	*WP2: Industrial design – a new approach to composite products: CSA measures*
Related Task(s):	*T2.1. Short-term staff exchanges and expert visits for the acquisition of know-how and experience in the field of design.*
Author(s):	*Nawar Kadi and Vijay Kumar*
Dissemination Level:	*Public*
Due Submission Date:	*31/10/2023*
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Abstract:	*The main objective of deliverable 2.1 was to transfer cutting-edge knowledge from the University of Borås in rapid prototyping methods and industrial design with a new approach to composite products to the Lodz University of Technology researchers. Under the framework of this work package and deliverable, four TUL researchers visited the University of Borås for four months, from March 2022 to June 2022, for a short-term staff exchange; each researcher stayed in Borås for two months and conducted research under different micro-project titles which are linked to work package two. As part of this deliverable, an immense knowledge exchange was obtained between the consortium partner universities and this know-how will be also shared to the business and science communities of Lodz University of Technology as part of task 2.2 and task 2.3 under the work package 2 in the form of training.*

1 The Methodical Recommendations on rapid prototyping methods for business and science community

A composite material comprises one or more discontinuous (reinforcement) phases embedded in a continuous (matrix) phase such that the former is usually stronger than the latter. The traditional way of manufacturing involves impregnating the matrix phase into a reinforcement phase that may be molded into the required geometry of the final product. The reinforcement material can be in the form of discrete particles, continuous fibers, as well as having a fibrous network in the form of textile preforms. The conventional route of composite manufacturing involves combining the reinforcement material and composite in two separate processes through conventional manufacturing process (e.g. manufacturing textile preform involves weaving, knitting, or braiding depending on the structure of the preform). Often, the preform is shared into the required geometry using the design manipulation in the preform fabrication process or by forced shaping using mold before impregnating the matrix into it to give the final shape of the component. While the conventional manufacturing process is longer in terms of the number of steps followed in the process, it is sometimes difficult to fabricate the preforms or the final composites in the required geometry or shape, or the final composite fails to meet the required performance behavior due to the inflexibility of the conventional manufacturing process.

Rapid prototyping (RP), also known as additive manufacturing, refers to a new class of manufacturing process that involves layer-wise or incremental fabrication of the structure layer-by-layer. It focuses on directly fabricating the required shape or depositing the material in the required final shape or geometry through some extrusion process, which gives speed, greater flexibility, and control for prototyping and production. Hence, unlike conventional manufacturing, rapid prototyping focuses on the controlled flow of material in a controlled and predefined path or model, which involves the advanced development of a 3D virtual model of the shape of the final component created utilizing computer-aided software or 3D scanning. Figure 1 shows a brief comparison of the steps in part formation by rapid prototyping through additive manufacturing vs the conventional process of milling (i.e. creating the final shape by removing the extra material, also known as subtraction as opposed to addition in additive manufacturing) and molding (i.e. using a mold for creating the final shape).

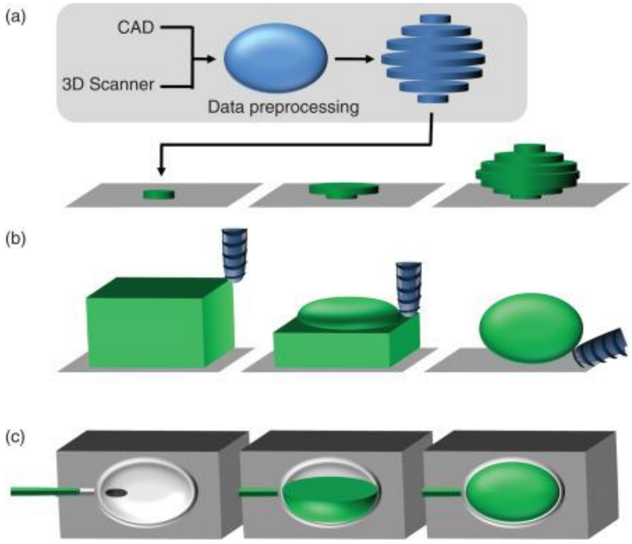

Figure 1: Rapid prototyping compared to prototyping through (a) milling and (c) molding processes. (Gurr and Mülhaupt, 2012)

RP offers a lot of advantages over the conventional counterparts in terms of greater flexibility in terms of design complex shapes, and control, but also reducing prototyping time and material waste. However, RP possesses limitations in being expensive for high-precision component fabrication, and the properties of the final parts is often inferior to those of conventionally produced counterparts.

In general, composite material fabrication through rapid prototyping can be adopted in three different ways, namely *discrete interface composites*, *porous media composites*, and *blended composites* (Gibson et al., 2009). Discrete interface composites involve layering different materials next to each other with or without bounding materials. *Porous media composites* involve fabricating a porous material in which a secondary material is infiltrated, which forms a composite when the latter solidifies. Depending on the characteristics of the secondary material, solidification may take place instantly or over time or may require further processing. *Blended feeds* on the other hand combine two materials (eg. reinforcement and matrix) before or during the extrusion/fabrication process. The control over the mixing of the material during the extrusion process gives greater control and possibility for gradient properties in the final product, which is not feasible in the conventional counterparts.

Further rapid prototyping via additive manufacturing can be divided into different types based on the process and material, as shown in Figure 2.

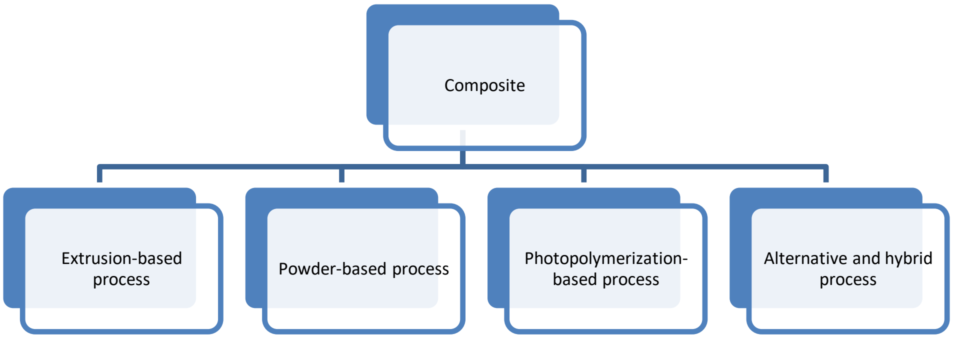

Figure 2: Different types of rapid manufacturing processes for fiber composites. Compiled from: (Yuan et al., 2021).

The extrusion-based process involves fabricating layer-by-layer 3D components using extruding a feedstock material through an extruder or fine nozzle by external pressure. The feedstock material can be in the form of thermoplastic filaments or pellets with short fiber mixed into them to form composites. Parameters such as feed rate, melting temperature of the feedstock material, chemical composition, short fiber characteristics and concentration in the feedstock, depositing speed etc. affect the properties of the final composite material.

The powder-based process involves depositing the powers in a layer-by-layer manner and based on the required final geometry, selectively sintering, or bonding the material with the deposition of the layer. For the fabrication of short-fiber composites, short fibers are mixed with powers and when the power mix solidifies, it automatically creates a composite material. Powder-based process can be further divided into different categories based on the process used for solidification.

The photopolymerization-based process, on the other hand, involves the process of turning highly-flowable or liquid resins into solids by the action of photopolymerization. The process usually uses UV-curable photopolymers such as epoxy and acrylic resins as feedstock materials which have high flowability and wetting effect. High flowability allows selectively dropping the material with high accuracy and tiny quantities that allow the formation of composite by voxel-to-voxel printing, which provide high freedom for design and manufacturing.

Finally, the alternate and hybrid process approach involves adhesive-coated layers, such as thermoplastic and thermos curable sheets used as feedstock material that are joined together and cut to form the final 3D shape. This is called the hybrid approach as it involves addition (ie. adding layers of laminates) and subtraction (ie. cutting and removing deposited layers as per the 3D shape contours) process, which harnesses the advantages of both routes. For example, while it is difficult to produce complex shapes as fabrication involves a layer-by-layer lamination process, it provides the advantages of fabricating relatively large shapes and objects, with higher speed and low price.

A comparison of the advantages and disadvantages of the above-mentioned processes is shown in Table 1.

Table 1: Advantages and disadvantages of different types of rapid manufacturing processes for fiber composites. Source (Goh et al., 2019; Zindani and Kumar, 2019)

Type	*Advantages*	*Limitations*
Extrusion-based process	Low cost, easy fabrication, multi-material capability	Layer-by-layer effect Nozzle clogging due to high concentration or volume of fibers
Powder-bed process	Fine resolution, high loading of reinforcement, unused power can be reused again.	Slow manufacturing, expensive, high porosity, limited to short fiber use.
Photopolymerization-based process	Fine resolution, highly isotropic effect due to random fiber orientation	Limited material choices, possibility to use limited fiber concentration, UV penetration issue
alternate and hybrid process	Low cost, high mechanical properties, no postprocessing required.	High wastage of material, difficult to produce complex shapes

As the demonstrative cases for the development of natural fiber-based polymer composites, two techniques were used in the microprojects carried out in SustDesignTex, ie. conventional rapid route, and additive manufacturing as rapid prototyping, as shown in Figure 3.

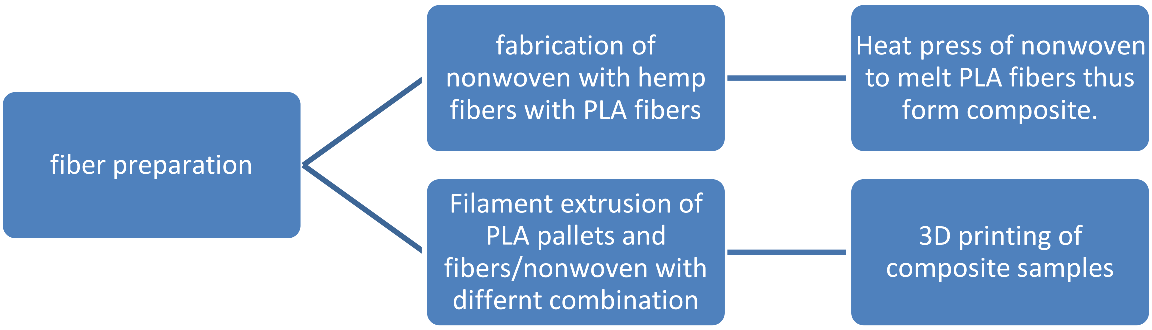

Figure 3: Plan for fabrication of fiber composites through shortening of the process by using nonwoven-based reinforcement in the conventional manufacturing process and additive manufacturing via 3D printing that uses fiber-mixed filaments.

As a composite material consists of fiber reinforcement and matrix, the route for rapid fabrication of the composite materials involves using the components that have a shorter route for manufacturing. For example, the fiber reinforcement used in the composite can involve different structures namely, woven, nonwoven, knitted, and braided structures. Among all, nonwoven structures is a process of fabrication of web-like structures that are converted from laying a web of fibers and bonding them to impart strength. Unlike woven or knitted structures which involves a series of operation between the fiber and textile structures, nonwoven can be produced from fibers in a one-step process, thus having the possibility for quick production. Not only having quicker production of the nonwoven substrate nonwoven structures also possess high porosity that facilitates matrix impregnation during the manufacturing process. Nonetheless, certain limitations need to be considered while selecting them for the right end-use applications. This includes limited stiffness performance due to random alignment of fibers and usually lower volume fraction that is required for high-strength applications.

Table 2 shows a relative comparison of the various textile preforms.

Table 2. Summary of advantages and limitations of nonwoven preforms as compared to textile structures for composite applications [source: (Rawal et al., 2023)].

Type	*Advantages*	*Limitations*
Nonwoven preforms	• Possess high porosity, which facilitates resin transfer during the composite fabrication process. • Direct fiber preforming of nonwoven preforms allows production with minimum waste and high repeatability.	• Possess relatively lower stiffness performance and strength. • Usually possess lower fiber volume fraction than usually required for structural composites.
Woven preforms	• Possess high strength and dimensional stability. • 2D woven preforms possess better in-plane properties and drapability. • 3D woven preforms possess improved out-of-plane properties and robust structures with high interlaminar strength and damage tolerance. • Possibility to produce near-net shapes with appropriate weft insertion methods and jacquard mechanisms.	• 2D woven preforms possess low transverse and out-of-plane properties. • Compared to 2D woven preforms, 3D woven preforms possess lower in-plane properties and poor drapability. • Limited tailorability for off-axis properties.
Braided preforms	• Possess excellent shear resistance, and high strength and stability characteristics with increased resistance to impact damage. • Offer a good balance in off-axis properties. • Can be produced in near-net shapes for complex components with varying cross-sections.	• Maximum preform size is determined by the machine size.
Knitted preforms	• Possess stretchability, drapability, and formability. • Can be fabricated in complex shapes and variable widths. • Quick and easy change of yarn during manufacturing.	• Lower in-plane stiffness and strength. • Extensible and unstable structure. • Loop structure can lead to distortion during the composite fabrication process.

In the demonstrative case, a nonwoven substrate is fabricated in the first stage that mixes two fibers namely hemp fibers and PLA fibers, and fibers are bonded in the nonwoven-web by needle punching process. In the second step, the nonwovens are heat compressed at 2 MPa and 190^{o}C for 7 min. As PLA has melting temperatures below 190^{0}C, the heating process melts the PLA fibers forming a composite with hemp as reinforcement and PLA as matrix.

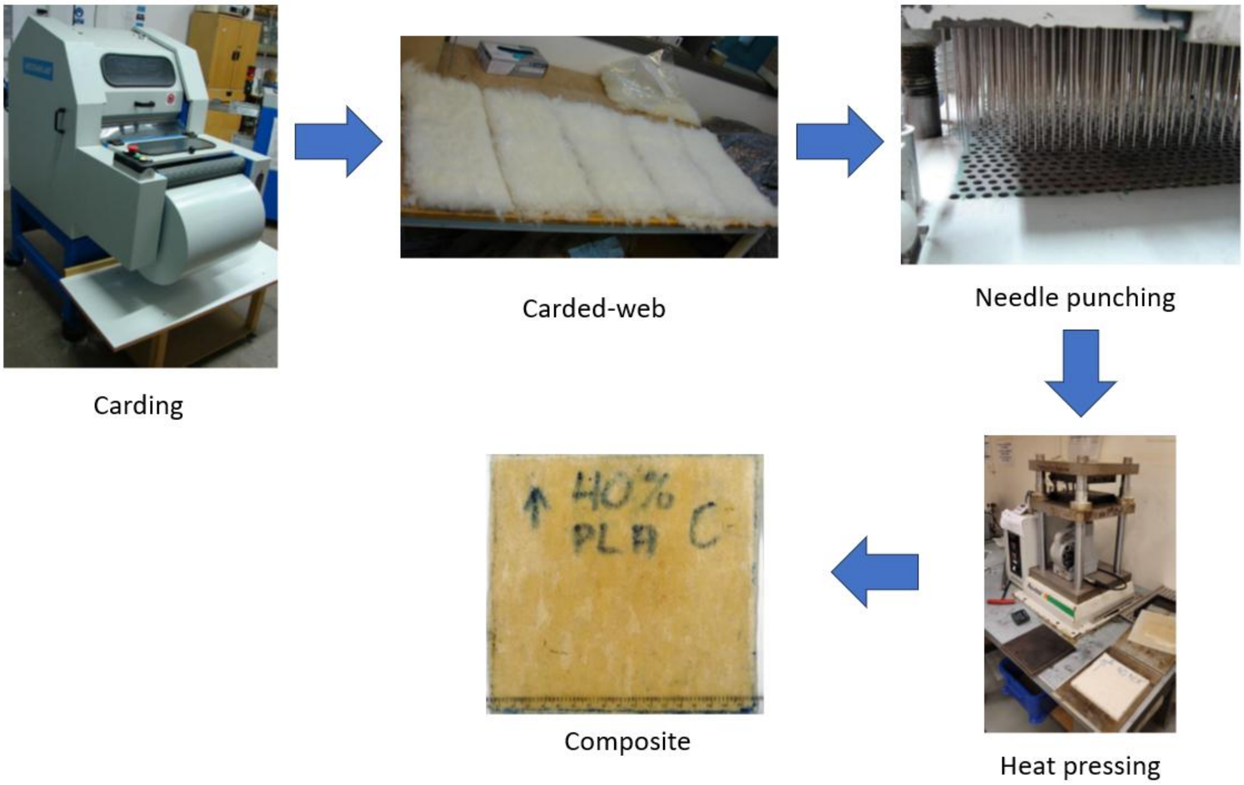

*Figure 4: Rapid composite manufacturing through nonwoven reinforcement and heat-pressing process. [Source: **Microproject 1** report].*

The other route for the formation of composite followed in the project involves additive manufacturing where the short fibers are mixed with PLA pallets and filaments in different compositions and processes, followed by 3D printing of the composites. While the possibility to print complex shapes with relatively good precision is one advantage of this process, the size of the composite and its mechanical properties. In the demonstration project, different combinations were carried out as per the workflow shown in Figure 5.

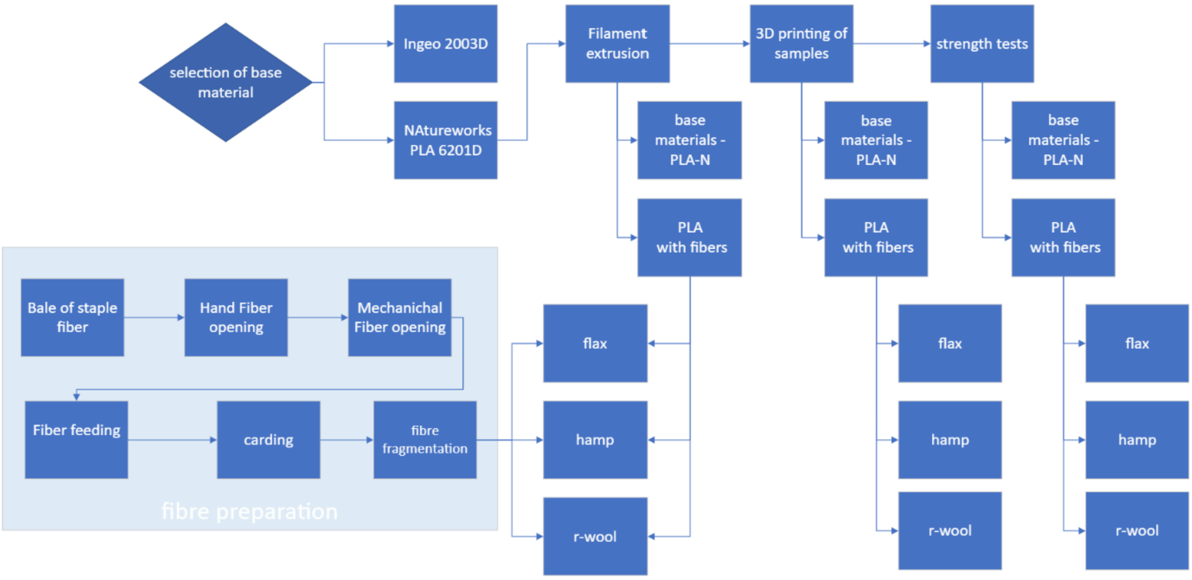

Figure 5: Methodological approach for fabrication of fiber composites by 3D printing-based additive manufacturing. *[Source: **Microproject 2** report]*

Challenges faced during the fabrication process are listed in Table 3.

*Table 3: Challenges in preparation of filaments for additive manufacturing of polymer composite. [Source: **Microproject 2** report]*

Preparation	*Problem/issues faced*	*Mitigation strategy*
Extrusion of pure PLA filament from pellets. (without fibers)	During extrusion, a problem was noticed with keeping the diameter of the fiber constant. Changes in the cooling method helped somewhat.	Elimination of the process occurred only at the end of extrusion of all blends. After about a month of testing and contacting companies involved in filament production lines, melting pumps were excluded from the process line and the correct nozzle diameter was selected, which solved the problem. Water cooling was also maintained.
Extrusion from pellets with fibers added in the process of backfilling the extruder.	During extrusion, a problem was noticed with the uniform dispersion of the fibers in the produced filament, which caused the filament to break as well as locally increase the brittleness of the material.	We have undertaken work to eliminate this problem. Using a combination of fibers and PLA by mechanical activation.
Extrusion of filament from granules with the addition of fibers combined by joint milling.	It was not possible to prepare a mixture with a concentration of more than 3%. The fibers that did not "stick" to the pellets during the	We have undertaken work to eliminate this problem.

	extrusion process floated in the feed hopper making extrusion difficult.	Using a combination of fibers and PLA by heat activation.
Extrusion of filament from pellets made from pellets compressed with fibers	The disadvantage of this method appeared to be uneven distribution of the polymer, especially in samples with a polymer content of 10% by weight. In contrast, a more even distribution of the material was observed in samples with a content equal to 20%.	We have undertaken work to eliminate this problem. The use of combining fibers with PLA by thermal activation with prior preparation of the polymer film

The microproject results were applied to fashion design and will be published in three review papers.

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