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ScienceDirect

Procedia CIRP 66 (2017) 317 – 322

www.elsevier.com/locate/procedia

1st Cirp Conference on Composite Materials Parts Manufacturing, cirp-ccmpm2017

Material extrusion of continuous fiber reinforced plastics using commingled yarn

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Abstract

At the University of Twente research has been executed on Additive Manufacturing using continuous fibers based material extrusion. A pultrusion based process has been developed to transform readily available commingled yarn to a polypropylene (PP) E-glass filament. A deposition device has been developed that among others includes a novel low cost fiber cutting device and a modified deposition strategy. Test samples were printed with a flexural modulus of 800% compared to 100% PP samples. Further void percentages up to 20% were found in the printed test samples. Future reduction of this void percentage will further increase the obtainable flexural modulus.

Peer-review under responsibility of the scientific committee of the 1st Cirp Conference on Composite Materials Parts Manufacturing

Keywords: Rapid prototyping, Fiber reinforced plastic, Continuous fiber;

1. Additive manufacturing using fiber reinforced plastics

Additive manufacturing (AM) is the name of a group of processes that are able to produce very complex geometries at low labor and production costs. To establish this the desired part geometry is approximated by subdividing the shape in many 2D layers; more layers ensure better product quality but also increases production time. AM machines produce these layers one by one. The tool that shapes/deposits the material is positioned above (or below) the layer that is produced. As the tool can move freely to any position, the theoretical complexity that can be achieved within a layer, and with that within the product, is theoretically unlimited. Also, as the movement of the tool is not obstructed by the product, the work preparation process, from the 3D design of the product to the control of the production machines, is relatively straightforward and can be 100% automated. These characteristics are among the main benefits that have ensured the recent grow of interest in AM [1]. Some of the drawbacks that have been reported for AM processes are the high surfaces roughness's that stem from the layered building approach, the relatively low production speeds, the high building cost for non-complex parts, the limited freedom in material selection when compared to other manufacturing techniques and the relatively low strength of parts produced with AM techniques [1].

Fiber reinforced plastics are more and more used when among others a high strength to weight ratio is needed (aerospace, automotive). Classic processes for part production using continuous fiber reinforced plastics use mold and mandrel based processes like compression molding, mandrel wrapping, filament winding and wet layup. In general, these processes are labor intensive and restrictive in the geometries that can be obtained. Less labor intensive process variants like Automated tape laying (ATL) and automated fiber placement (AFP) use robots but still to place the fiber/matrix sheets into molds. Currently no classic production processes for continuous fiber reinforced plastics exits that share the benefits of additive manufacturing (automated production of complex products at low costs). Based on shared characteristics like material type, deposition and material fusion methodology used, the ASTM (American Society for Testing and Materials) in 2010 has defined 7 AM process groups [2]. None of these

Peer-review under responsibility of the scientific committee of the 1st Cirp Conference on Composite Materials Parts Manufacturing
doi:10.1016/j.procir.2017.03.367

groups have composite materials and products as their common denominator, although some have process or material variants that use additives to enhance properties of the finalized product. Based on that observation it can be concluded that there is a need for the development of AM processes using continuous fibers for products that are geometrically complex and for which the functionality can be characterized by high strength, high stiffness and low weight.

2. State of the art in AM with continuous fibers

When fibers are used in AM these additives fibers are often used to enhance the mechanical, electrical or thermal properties of parts [3]. On a high level of abstraction 3 strategies can be identified in which fibers are used to produce parts that have mechanical properties that surpass those of the base materials. These strategies themselves are often applicable within several of the 7 AM process groups.

1. Short, chopped fibers are often mixed in with existing AM materials to increase mechanical strength of the resulting parts. These fibers are included in processes like Fused deposition modeling (FDM), Stereo lithography (SLA), Selective Laser Sintering (SLS) etc. Tensile strength improvements up to 194% are obtained using chopped fiber additions [3].
2. It is also possible to directly use fiber reinforced sheets to build 3D products. Impossible objects [4] has developed a process on which inkjet technology is used to print polymers on sheets of fibers. After stacking and oven consolidation a mechanical or chemical process is used to remove the unwanted uncoated fibers; the desired part geometry remains. A tensile strength increase by a factor 10 is reported by the company [4].
3. Finally, AM parts can also be reinforced with continuous fibers. Research focusing on these processes are discussed in more detail in the next subchapter.

2.1. State of the art in AM part reinforcement with continuous fibers.

In recent years some research has been conducted that focused on development and characterization of new methods for additive manufacturing based production of complex geometries with continuous fibers reinforcement.

Melenka [5] studied the elastic behavior of test specimen printed with the commercially available MarkOne 3D printer from Markforged [6]. This printer creates the base geometry in Nylon while 3 reinforcement options are available; Carbon Fiber, Fiberglass and Kevlar. The printing/reinforcement strategy used is printing parts while adding concentric rings of fibers that follow the components outer geometry. Tensile test samples were printed using Kevlar reinforcements. The geometry of the samples limited the number of concentric rings that could be printed to a maximum of 5, which in its turn limited the maximal volume fraction of fibers to be used. The experimentally determined elastic modulus was found to be 1.7, 6.9 and 9.0 GPa for Kevlar volume fractions of 4.0, 8.1 and 10.1% respectively. In these tests it was observed that the location of the start of the filament placement was also the location of failure during testing. This might be explained by the limited number of concentric rings and thus the relatively large effect of this local distortion.

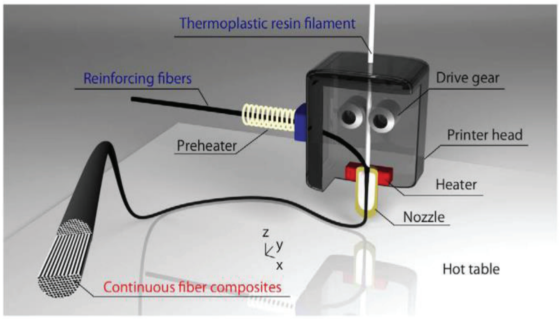

Fig. 1. 3D printing device as developed and used by Matsuzaki et al.[8]. To increase printing flexibility, it uses two separate material strands that are joined in the heater of the extrusion head.

Klift et al. [7] also used the MarkOne [6] to study the effect of fiber reinforcement on the mechanical properties of plastic parts. The printed tensile test specimens had a carbon fiber volume fraction of 1.0% in a nylon matrix material. The resulting mechanical properties were lower than expected according to the rule of mixing used for composites. These low mechanical properties were contributed to the delamination of the layers and the formation of voids during deposition. Some solutions were suggested to prevent these problems from happening (preheating of the carbon fibers, changing the temperature of the print bed, decreasing the diameter of the nozzle) but not validated.

Matsuzaki et al. [8] developed a non-commercial variant of the FDM material extrusion process where both the reinforcement and the matrix material are fed into the extruder as separate material flows (fig. 1). Experiments focused on testing both carbon and natural fibers (jute) as reinforcement while using Polylactic Acid (PLA) as the matrix material. For both fiber types an increase in the mechanical properties was observed. The tensile modulus (19.5 GPA, +599%) and strength (185.2 MPA, +435%) of the carbon fiber reinforced specimen (6.6% volume fraction fibers) are significantly higher when compared to 100% PLA samples. Also 3-point bending tests were executed, but the results were estimated to be questionable, as the distribution of the fibers was non-uniformly over the cross section.

Li et al. [9] and Tian et al. [10] conducted experiments similar to Matsuzaki [8], as they used separate material bundles (Carbon fiber and PLA matrix material) to create test samples. Li [9] created test samples with 34 volume % fibers. As expected a significant increase in tensile strength (80 MPA; 185%) was found. The increase in flexure strength was only limited (59 MPA; 11%), which was contributed to the poor adhesion between PLA and carbon fibers. A second set of tests were conducted for which the surface of the carbon fibers was modified to increase the strength of the bonding interface between the PLA and the fibers. These samples showed significant increases in both tensile (225%) and flexural strength (194%) when compared to 100% PLA test specimen.