Fabrication of complex 3D composites by fusing automated fiber placement (AFP) and additive manufacturing (AM) technologies

Felix Raspall, Rajkumar Velu and Nahaad Mohammed Vaheed

Digital Manufacturing and Design Centre, Singapore University of Technology and Design, Singapore, Singapore

ABSTRACT
Automated fiber placement (AFP) is emerging as one of the advanced methods toward fabrication of polymer matrix based composite structures. This automated technique focuses on polymer composite manufacturing for use in a wide range of automotive and aerospace applications. The AFP process offers an elevated level of customization through the possibility of placing each individual tow at custom-designed trajectories. Additive manufacturing (AM) method, on the other hand, has the potential to fabricate functional end user parts of complex geometries, thus eliminating the need for costly tooling, multi-step processing and fasteners or joints. This paper will highlight the potential of fusing AFP and AM processes to fabricate complex 3D polymer based composite parts. A combination of these two processes suggests a promising option for composite materials development, improving composite structures in terms of complexity and customizability. The paper presents the adopted research methodology, background research, the design, development and set up of an experimental workcell that fuses AM and AFP, and the design methodology which is required to design complex composite parts using the proposed manufacturing process. Main challenges and opportunities are discussed, such as how restrictions of conventional composite production can be eased, and additional freedoms of design can be achieved.

Introduction
Fiber reinforced polymers (FRP) present distinct advantages over other material choices. FRP are light-weight, corrosion resistant. They exhibit high energy absorption levels [1–3] and allow for customized reinforcement design. For these reasons, aircraft, aerospace and automobile industries continue to adopt and advance composite manufacturing processes to achieve levels of performance that exceed metallic counterparts [4,5]. The fundamental processing technologies for the fabrication of FRP are well described in the literature [6–8]. Among the various composite processing systems, the use of prepreg tapes is a well-established technique to produce composite components [9,10]. Prepreg involves coalescing fiber and matrix in a process line as an intermediate good, which are typically manually laid up and cured in an autoclave. However, the manual hand lay-up process requires intensive Labor, time and cost, and presents challenges in achieving adequate dimensional accuracy and repeatability [11]. In early days, manual layup was used to
produce composite structures in low and middle-volume quantities, while for large production volumes direct processing techniques were preferred [12,13].

To overcome issues derived from hand lay-up, the two main automation technologies were developed: Automated tape laying (ATL) [14] and automated fiber placement (AFP) [11], both suitable for the fabrication of composite structures using unidirectional prepregs. ATL and AFP are similar processing techniques, where ATL delivers wide prepreg tapes of around 60 mm wide [15] and AFP applies band of narrow prepreg tows of width typically smaller than 1” [16]. In 1974, ATL was used for composite components fabrication [17]. However, manufacturers faced technical limitations, including long processing times, dents or buckles in the produced parts, high material wastage and elevated processing cost due to its use of wide prepreg tapes. Subsequently, AFP systems were commercially identified as suitable processing technology in 1990 [18]. Further research propelled AFP control design and parameter investigations [19]. As a result, AFP became a mature processing method and was identified as the most suitable to produce high performance aerospace components [20]. MAGCincinnati, MTorres, Electroimpact, Coriolis and Broetje-Automation Composites are commercial manufacturers of AFP and ATL machines [21–24].

Automated fiber placement technology has undergone significant process improvement in the past decades. AFP process evolved to manufacture double-curved surfaces with the placement head automatically handling the start, stop and cutting of individual tows [25]. Initially, researchers focused on improving process reliability by reducing the splicing errors at the end of bobbin based on introducing the automatic splicing of tows, which increased the productivity [26]. AFP machines often place multiple slit tapes simultaneously, with up to 32 slits currently available. The placement head delivers the prepreg material from the spools into a compaction roller, where heat and force are applied to compact the material into the previous ply, eliminating voids. Further, to improve the quality of layup and tack levels, infrared and laser heating were identified as adequate heating sources to achieve rapid heating and elevated temperature lay-ups [27,28]. Research aimed to improve the raw productivity and reliability continues, because of several unresolved technical issues in the production process. Size constraints and reachability have been a limiting factor. Therefore, AFP work system has been improved by additional mechanisms such as gantry systems and robotic manipulators [29,30]. Large parts can be produced by mounting the placement head on a gantry system, but they require high capital investment. Later, automation research converged on robotic arms to drive the placement head, a cheaper set up but with a more limited building envelope [31].

Upcoming research centers on increased productivity and geometric complexity. In the last few years, the automotive and aerospace structure manufacturers are developing multi-robot plants or integrating the gantry axis with robots to increase productivity, with separate production units for operations. Consequently, researchers started investigating on the coordination and cooperation of multiple robots and other manipulators. Xiaoming et al. [32] simulated a designed collaborative system, modeling the motion, kinematics and trajectory using SimMechanics/MATLAB. Their investigation presents the design and analysis of a 13 degree of freedom (DOF) collaborative AFP machine which involves 6 DOF manipulator, a 6-RSS (Revolute Spherical Spherical) parallel robot and a spindle holding the mandrel (1 DOF) mounted on the platform of parallel robot. The result revealed that the use of a collaborative robotic workcell enlarged the AFP manufacturing workspace, simplified the trajectory planning and improved the production efficiency when compared with a 7 DOF AFP machine. Wells et al [29] integrated an off-the-shelf 6-axis KUKA robot with high speed 4-axis ultrasonic cutting gantry (UCG) and zone controlled vacuum table. The UCG was specified as a 30 kHz ultrasonic knife with maximum speed of 76 m/min.

Electroimpact’s modular AFP head technology was outfitted on a robot with the ability to switch from a full-table work zone to multiple work zones, allowing the workers to access the finished goods in one zone while the robot continues operation in the other, increasing the system’s utilization. Further, layup and final trim occurs on the same table. Coordination and cooperation between robots were controlled by Electroimpact collision detection and safety software using position information from both machines. In another paper, Electroimpact presents a robotic AFP process with off-the-shelf 6-axis KUKA Titan KR1000L750 riding on a linear axis and modular fiber placement head. The robot axes were enhanced with secondary position encoders. The modular fiber placement with onboard creel head was mounted on a tool changer, which allows automated change of the head. In both cases, Electroimpact used a Siemens 840Ds1 CNC control system for all process functions, robot motions and execution software, aiming to extreme positional accuracy and enhanced kinematics utilizing a high-order kinematic model [33].
Berend et al. [34] developed the general design of a modular laying head and validated the preliminary results based on process limits. The designed modular head solves the current industrial need of compaction optimization for complex-curved structures. The rollers were designed to adjust the height based on curved geometries and each pressure level is controlled to enable individual compacting pressure. Eventually, this modular design intends to achieve higher laying speeds and qualities and reduce process failures.

Beyond increasing productivity, AFP research focuses on precision. Automation systems’ precision is mainly defined through various process parameters and factors. The most significant factors which affect precision are vibration, process-induced movement, variation in temperature and controllability limits of the drive [35]. Therefore, studying the plant structure can increase production rate and part quality. To improve the system’s precision, Christian et al. [36] developed a new plant, processes and sensor system. The plant consists of novel robot-based, multi-head fiber placement facility, which coordinates eight layup units. A CAD-CAM simulation was developed to coordinate layups and deliver a time- and cost-effective manufacturing process. Further, comprehensive sensing system was included to enhance quality and productivity.

The aforementioned review reveals that the overall goal in AFP development is to increase productivity and precision. Improvements have been achieved through the development of software, machine layouts and materials and layup calibration. However, at present, productivity is already largely limited by part geometry and layup design constraints, secondary operations and down-time [37–39]. Research that identifies the solution for any of these constrains becomes critical. The research gap identified is: design and manufacturing of complex-geometry laminate parts with custom-design fiber orientations is a very challenging process and a key developmental area in AFP research. Typically, complex geometry parts are manufactured with fabrics and therefore present regular reinforcement patterns, while complex reinforcement patterns made possible by AFP technology have only been developed for simple geometry parts. Composite parts that offer both a complex overall geometry and a custom reinforcement pattern can lead to a new level of performance in composite parts.

Successful production of complex geometry parts with custom-designed reinforcement can be resolved through a hybrid manufacturing process that brings together additive manufacturing (AM) technology and AFP technology. The AM process provides geometric freedom and enables the creation of complex geometry tooling and molds [40]. The AFP process provides the actual composite manufacturing with fiber layout complexity.

AM is the most advanced technology to achieve complex geometry parts, produced layer by layer from 3D CAD information. There are number of key applications where 3D printing technologies is currently impacting composite structures manufacturing [41–43]. Among these, 3D printing of molds and tooling has recently become a noteworthy research area. Traditionally, mold tooling is based on metallic materials like aluminum, steel or Invar alloys [44]. More recently, fiber reinforced polymer materials and high temperature tooling board are also a prevalent choice. Irrespective of material, the main concerns in tooling manufacturing are the significant Labor, cost, wastage and duration for machining. Therefore, significant advantages can be achieved when using AM technology such as fused deposition modeling (FDM) for composite tool molding, including time and cost reduction, increased design freedom, rapid iterations near to part complexity, light weight tooling, simple transportation and storage [45].

So far, research on AFP technology has not considered the integration of AM process to improve the geometric complexity of composite structures. The current research focuses on the development of a workcell that combines AFP and AM into a hybrid system with two robots. One robot is dedicated to AM and other is used for AFP process. These two robots work together: the AM robot fabricates the mold on which the AFP robot lays the prepreg tows up. The main objective is to improve the design and production workflow of composite parts, covering the development of an effective design environment for fiber layout, a functional fiber-placement work-cell and a robust machine control system.

**Design and development of AM robust system**

Additive manufacturing has the unique ability to fabricate highly complex geometries without tools, which can be light and stable [46]. There are seven distinct additive manufacturing technologies used for rapid prototyping and manufacturing purposes: vat polymerization, sheet lamination, material extrusion, material jetting, binder jetting, directed energy deposition and powder bed fusion. AM provides a high degree of design freedom, optimization and integration of functional features and enables the manufacturing of small batch sizes at economical unit costs [47–51]. AM systems are typically equipped with three linear motion axes to position
the processing tool head relative to the building platform in a translational motion. The process paths for each slice are planned based on slicing a CAD model of the part [52]. Recently, research combines robotics and AM to enable larger build volume and the integration of other production processes such as machining, inspection, surface finishing, sanding and painting [53]. Consequently, integrating AM with robots can develop a whole production architecture around robotics.

**Methodology**

To increase the potential and flexibility of the robot-based AFP process, AM is proposed as the method to fabricate geometry-specific substrates that support the prepreg layup process. In the past, the tool head is mounted on the robotic arm for layer-by-layer fabrication [54]. In this current research, the robotic arm positions the bed. While there are a variety of AM technologies, many of which have potential relevance toward production of composite parts, the focus here is on the extrusion-based technology patented as FDM [55]. The FDM technology involves extrusion of thermoplastic materials under controlled conditions [56] to fabricate substrates for AFP. This research proposes a stationary extrusion process approach, where thermoplastics pellets are melted and extruded in the form of strings, with a moving build plate mounted on a robot [57]. The main advantage of this setup is twofold: manufacturing of high complexity structures and seamless connection with the AFP process chain. Furthermore, by using robots it is possible to realize the modeling process in free, determinable directions. Based on this processing method, it is necessary to consider and analyze basic process challenges like part adhesion to the platform as well as dimensional stability. To develop the described process approach, the paper presents the overall AM and AFP workcell robust system.

**AM robust setup**

The AM work station combines multiple components, including a thermoplastic extruder, a heated print bed or table, and an industrial robot. Figure 1 shows the setup, while Table 1 summarizes its technical specifications. The stationary extruder is an MDPH1 (Massive Dimensions). It takes raw material in the form of pellets, which are melted in its heating chamber before oozing out of the nozzle with a consistent flow. The build plate receives the melted material and moves to support the built of the object. Movements are controlled by an ABB IRB 6620 industrial arm robot, through pre-configured and programed paths along defined target points. The surface of the build plate is made of aluminum and is heated to minimize warping issues generally associated with large prints produced through the FDM process. Heat is provided through a heating element manufactured by Keenovo Silicone heaters, which provides a constant surface temperature. Its temperature can be maintained as per required, slightly below the glass transition temperature \(T_g\) of the polymer pellets being processed. The structure of the build plate is made up of an aluminum frame and a plywood substrate. The operation of the extruder and heated bed are directly controlled through digital signals from the industrial robot controller ABB IRC5.
Design and development of AFP robust setup

As mentioned, earlier, the robotic fiber placement process presents numerous advantages that include consistent consolidation of material, fiber orientation control and high degree of repeatability. Figure 2 shows the AFP work station, designed and built as a test bed for experimental investigations as well as for final composite part fabrication. The AFP head is designed to be mounted on a KUKA KR 60-3 industrial robot. The robot follows preprogrammed paths along target points, based on where the fibers are to be laid over a mold. The AFP head’s controller (Beckhoff PLC) has a communication line established with the industrial robot’s controller. This allows for its control through program instructions via the industrial robot’s KUKA KR C4 controller. The fiber placement head dispenses pre-impregnated fiber tows row-after-row to form a laminate of composite material. The process is repeated to build multiple plies of same or different orientations.

The AFP head comprises of different operating components that include the backing film roller, spool holder, deflection roller, drive unit, cutting unit and infrared emitter (heating unit) as shown in Figure 3 and specified in Table 2. The fiber placement head intakes the impregnated fiber tow from a standard Hoffner spool and dispenses it through the outlet, after going through a series of rollers that serves to maintain a certain amount of tension for a smooth layup process. The backing roller removes the backing film, if present, and the pneumatic cutting blade unit cuts the output tow at desired moments to achieve the designed lengths. The heating

| Sl No | Component          | Specification       | Data              |
|-------|--------------------|---------------------|-------------------|
| 1     | Pellet Head Extruder | Model              | Massive Dimension (MDPH1) |
| 2     | Heated Bed (Keenovo) | Max Temperature     | 450 °C            |
| 3     | ABB IRB 6620       | Max Temperature     | 200 °C            |
| 4     | ABB IRCS           | Dimensions          | 600 × 1000 mm     |
| 5     | Stationary Frame   | Repeatability       | ±0.03 mm          |
|       |                    | Reach               | 2.2 m (without Tool) |
|       |                    | Payload             | 150 Kg            |
|       |                    | Weight              | 900 Kg            |
|       |                    | Dimensions          | 3.0 × 2.2 × 1.0 m  |

Figure 2. Automated fiber placement (AFP) workcell.

Table 1. Specification of the components in the AM station.
source is an IR-Lamp, which heats up the exiting tow to specified temperatures up to 250 °C, bringing the tow to a semi-curing state, thereby increasing its tackiness so that the tow consolidates easily on to the mold. Then the compaction roller applies a specified amount of force, which eliminates trapped air and promotes filling of voids between the tows and the substrate material. Through the above mentioned steps, properties such as viscosity of the matrix resin, bonding between plies and tows, residual stresses, voids and warping can be controlled.

**Fusing AFP and AM technologies**

The AM and AF robust setups are integrated into a single station as shown in Figure 4. The AM station consists of a stationary extrusion system and a robot holding the build plate. The AFP system consists of the fiber placement head mounted on an industrial robot. The system setup was designed such that the two segments can work as a single integrated collaborative workcell, where the two processes are combined, as well as independent workcell for AM and AFP processes. This strategy presents two advantages. On the one hand, it facilitates parallel research on both processes. On the other, during production, it increases productivity as some manufacturing processes may only require either mold fabrication (AM) or composite production (AFP).

**Integration of AM and AFP workcell**

With objective of producing complex three-dimensional composites structures, the first step in the workcell development process was to identify and address the challenges in integrating the two manufacturing technologies (AM and AFP). Four key...
issues were identified: (a) complex mold shapes required more complex fiber placement process, (b) smooth transfer of mold between work stations, (c) toolpath generation and simultaneous execution and (d) compatible combination of raw materials.

In most AFP systems, the fiber placement head must remain perpendicular to the working surface, which induces process limitations and constrains on maneuverability. By adopting two industrial robots into a single system, one holding the layup table and the other holding the fiber placement head, the complex paths required during layup on complex mold shapes can be achieved. The level of complexity achieved is far better than that is observed from most other AFP systems with stationary molds.

To eliminate the need to transfer 3D printed molds into the fiber placement station’s layup table, where the next phase of product fabrication takes place, the printing approach was changed. In our design, unlike most FDM printers, where the extruder moves along the XY planes, the print table would move with respect to a stationary extruder. The advantage of doing so is the possibility of moving the print table with the printed mold/part directly into the fiber placement station once the mold has been printed. This eliminates the need for a layup table, saves mold removal and transfer time, and zero position calibration requirement (regularly done on AFP layup table). The compromise made by adopting this approach was the larger transverse space required by the print table as compared to the smaller space required by an extruder, to print a mold of the same size.

The third fundamental challenge in the development of a functional workcell was the generation, programing and execution of the complex motion sequences. The AM toolpath planning and program generation is done through the slicing of a model of the part. The AFP planning required custom geometric calculations to solve the orientation of the head throughout the toolpath, considering the direction of the fiber and the normal direction of the part at every point. The toolpath planning and robot programing were developed as a script within a commercial computer-aided software.

Another challenge addressed was the prepreg-to-mold material compatibility due to inherent heat propagation processes. The fiber placement process involves the application of heat, up to 250 °C, as the prepreg tows are being laid, which could potentially deform or damage the mold if the material is not resistant to such elevated temperatures. To resolve this issue, high temperatures polymers such as Ultem (PEI) and PEEK were selected as the mold material. Only prepreg tows requiring a maximum of 250 °C curing temperatures were used.

**Toolpath planning and simulation**

Toolpath planning for the two stations were solved within the modeling environment of Rhinoceros, visual programing Grasshopper and inverse-kinematic solver HAL. The advantage of such a platform is the rapid pace at which the programing of custom algorithms to determine complex toolpaths can be achieved. Once the robot code is obtained, it is verified on the robot’s native simulation environment before running it on the workcell.

In traditional FDM printers, the model to be printed is usually sliced using a slicing software, followed by g-code generation that specifies toolpaths.
to be followed in a layer-by-layer fashion. Due to the stationary extruder configuration in our design, rapid codes (ABB programing language) generated to produce toolpaths, are mirror images of those when produced by a general slicer/slicing software, although in the same layer-by-layer technique. The motion planning requires an inversion of the toolpath, as shown in Figure 5.

Initial experiments on AM process

Initial samples, as shown in Figure 6, were printed using ABS and PLA, to better understand the influence of process parameters on melt flow behavior and further on inter-layer fusion and coalescences. Of all the influencing parameters, including material properties, part bed characteristic, and process parameters, among others, the nozzle diameter, melt temperature and build bed speed were found to play a more significant role in determining the properties of the 3D printed model [58]. Initial experimental trials were conducted to produce multi-layer samples with nozzle diameters of 1.75, 2 and 3 mm. Extrusion temperature and rate were varied between 205 ± 10 °C (PLA), 235 ± 10 °C (ABS) and 3–15 mm/sec, respectively, to identify the optimal process parameters for fabricating better parts. Heat bed temperature was set at 60 and 90 °C for PLA and ABS, respectively. Subsequent samples were printed using Ultem (PEI) with the processing conditions of: heat bed temperature of 140 °C, extrusion temperature of 350 °C and extrusion rate of 2lbs/h. The stationary frame was partially enclosed to maintain the temperature in the build volume, required for high temperature polymers to adhere to the print surface as well as to reduce contraction induced defects.

Initial experiments on AFP process

Initial experiments were carried out to understand the relationship between process parameters and the quality of the panel obtained in order to optimize the process. These experiments were performed with both thermoplastic and thermosetting towpregs at angles of 0°, 45° and 90° on the base material. The flat panels shown in Figure 7 were constructed successfully with minimal gaps between tows. The processing conditions used for thermoplastic composite prepreg tapes were: 20dN roller force, 60 °C heat bed temperature, 245 °C induced heating (100% of 250 W, IR) and layup rate of 0.78m/min. The thermosetting prepreg tows were processed with the conditions of: 15dN roller force, 85 °C heat bed temperature, 178 °C induced heating (80% of 250 W, IR) and layup rate of 0.45m/min.

For the fiber placement process, heating of tows and the compaction force were identified as the most influencing and significant variables. Proper coalescence could be achieved with the provision of enough heat to the tows, thereby increasing its tackiness. Optimizing the compaction force to be applied would remove trapped air and fill voids between the tows.

Common issues observed in both thermoplastic and thermosetting material tapes are (a) peeling/detaching of tapes from ply and (b) contraction of tapes. The former issue involves slow peeling of the previously placed tape from a ply, off the mold. This occurs due to insufficient friction force underneath the compaction roller. The latter issue involves the forming of gaps between laid tapes in a single ply due to contraction. The reason to the occurrence of this issue usually needs further investigation. Although, possible explanations for this issue include slight tilt in the alignment of fiber within the tape which induces lateral forces when tension is applied during the layup process (defect incurred during tape production), and the influence that heat has on the viscosity of the resin in the tape.

The peeling defect was observed from the initial layups obtained from the AFP station, and was corrected by regulating processing conditions that include compaction force, transverse time/layup rate.
and induced heat temperature. Gaps between tows due to contraction were also observed in the initial experiments. This issue was partially resolved by fine-tuning the robot programming to account for the contraction by a percentage. Thereby, having tapes laid slightly closer to each other, but not close enough to cause overlaps.

**Summary and future prospects**

This paper presents a new method or technology for the design and robotic manufacturing of three-dimensional composite components by integrating two processes: AM and AFP. Initial research review collected during the design of the integrated AM and AFP workcell system has been presented, along with the identified research gap in the process of fabrication of composite structures. The technical concept and the sub-components of the workcell system have been described. Also, the design of workcell integration, initial trials and optimization steps, toolpath planning and robotic operational approach has been described. Key identified benefits of the fused AM and AFP work-system include: low mold production time, mold compatible with prepreg tapes only requiring up to 250 °C curing temperatures and, fully automated production of composite parts and components. Further investigation and improvements to achieve better quality molds include programing of algorithms to optimize layup on complex shapes and reduce defects in composites manufacturing.

**Disclosure statement**

No potential conflict of interest was reported by the authors.

**References**

1. Bakis CE, Bank LC, Brown V, et al. Fibre-reinforced polymer composites for construction—state-of-the-art review. J Compos Constr. 2002;6:73–87.
2. Fuchs ER, Field FR, Roth R, et al. Strategic materials selection in the automobile body: economic opportunities for polymer composite design. Compos Sci Technol. 2008;68:1989–2002.
3. Thornton PH. Energy absorption in composite structures. J Compos Mater. 1979;13:247–262.
4. Fuchs ERH. The significance of production cost inputs in regional technology choice: composite automotive body-in-whites in the us versus china [Doctoral dissertation]. Cambridge, MA: Massachusetts Institute of Technology; 2003.
5. Mahieux CA. Cost effective manufacturing process of thermoplastic matrix composites for the traditional industry: the example of a carbon-fibre reinforced thermoplastic flywheel. Compos Struct. 2001; 52:517–521.
6. Thostenson ET, Chou TW. Microwave processing: fundamentals and applications. Compos Appl Sci Manuf. 1999;30:1055–1071.
7. Shofner ML, Rodríguez-Macías FJ, Vaidyanathan R, et al. Single wall nanotube and vapor grown carbon fibre reinforced polymers processed by extrusion freeform fabrication. Compos Appl Sci Manuf. 2003;34:1207–1217.
8. Soutis C. Carbon fibre reinforced plastics in aircraft construction. Mater Sci Eng A. 2005;412:171–176.
9. Mignery LA, Tan TM, Sun CT. The use of stitching to suppress delamination in laminated composites. In ASTM Editors. Delamination and debonding of materials. USA: ASTM International; 1985. Online ASTM publications Source: STP36315S.

10. Mouritz AP, Bannister MK, Falzon PJ, et al. Review of applications for advanced three-dimensional fibre textile composites. Compos Appl Sci Manuf. 1999; 30:1445–1461.

11. Dirk HJL, Potter KD, Eales J. A concept for the in-situ consolidation of thermostet matrix prepreg during automated lay-up. Compos B Eng. 2013;45: 538–543.

12. Mohlin M, Hanneberg M. Chassis component made of composite material: an investigation of composites in the automotive industry and the redesign of a chassis component; 2016.

13. Briggs PC, Jialanella GL. Advances in structural adhesives. In Dillard DA. Advances in structural adhesive bonding. Sawston, Cambridge, United Kingdom: Woodhead Publishing; 2010.132–150.

14. Crossley RJ, Schubel PJ, Warrior NA. Experimental determination and control of prepreg tack for automated manufacture. Plast Rubber Compos. 2011;40: 363–368.

15. Lukaszewicz DHA, Potter K. Through-thickness compression response of uncured prepreg during manufacture by automated layup. Proc Inst Mech Eng Part B. 2012;226:193–202.

16. Rastegarian Jahromi H. Characterization of damage in dry automated fibre placement (DAFP) carbon epoxy composites under tensile loading [master’s thesis]. POLITECNICO DI MILANO, Faculty of Industrial Engineering, Master of Science in Mechanical Engineering; 2015.

17. Beakou A, Cano M, Le Cam JB, et al. Modelling slit tape buckling during automated prepreg manufacturing: a local approach. Compos Struct. 2011;93: 2628–2635.

18. Marsh G. Automating aerospace composites production with fibre placement. Reinf Plast. 2011;55: 32–37.

19. Lopes CS, Seresta O, Coquet Y, et al. Low-velocity impact damage on dispersed stacking sequence laminates. Part I: experiments. Compos Sci Technol. 2009; 69:926–936.

20. Scelsi L, Bonner M, Hodzic A, et al. Potential emissions savings of lightweight composite aircraft components evaluated through life cycle assessment. Express Polym Lett. 2011;5:209–217.

21. McCarville DA. Evolution of and projections for automated composite material placement equipment in the aerospace industry [Doctoral dissertation]. Minnesota: Walden University; 2009.

22. Rudberg T. Increasing machine accuracy by spatially compensating large scale machines for use in constructing aerospace structures. SAE Int J Aerosp. 2013;6:206–222.

23. Giddings P, Di Francesco M. Reducing cost and risk in layup of convex corners using Automated Fibre Placement: A simulation led approach. The Second International Symposium on Automated Composites Manufacturing; 2015 Apr 23; Montreal.

24. Diersen T, Bloedorn C, Mehlenhoff T. (2010). Solution for dry-fibre-placement with a standard articulating robot system (No. 2010-01-1853). SAE Technical Paper. DOI:10.4271/2010-01-1853.

25. Izco L, Istaniz J, Motilva M. (2006). High speed tow placement system for complex surfaces with cut/clamp/restart capabilities at 85 m/min (3350 IPM) (No. 2006-01-3138). SAE Technical Paper.Warrendale, PA: SAE International.

26. Wehebee R. (2017). Modeling of Tow Wrinkling in Automated Fibre Placement Based on Geometrical Considerations [Doctoral dissertation]. South Carolina, USA: University of South Carolina.

27. Stokes-Griffin CM, Compston P. The effect of processing temperature and placement rate on the short beam strength of carbon fibre–PEEK manufactured using a laser tape placement process. Compos A Appl Sci Manuf. 2015;78:274–283.

28. Lichtinger R, Hörmann P, Stelzl D, et al. The effects of heat input on adjacent paths during automated fibre placement. Compos A Appl Sci Manuf. 2015; 68:387–397.

29. Wells D, Walker A. Integrating ultrasonic cutting with high-accuracy robotic automatic fibre placement for production flexibility. Proceedings of Society for the Advancement of Material and Process Engineering (SAMPE) Annual Conference and Exhibition. Seattle WA: SAMPE Tech.; 2014.

30. Solanki RS, Rattan KS, Chiu BA. Flexible computer integrated manufacturing system.

31. Ibrahim MY, Fernandes A. Study on mobile robot navigation techniques. In 2004 IEEE International Conference on Industrial Technology, 2004. IEEE ICIT’04. Hammamet (Tunisia): IEEE; 2004. Vol. 1, p. 230–236.

32. Zhang X, Xie WF, Hoa SV. Modeling and workspace analysis of collaborative advanced fibre placement machine. In ASME 2014 International Mechanical Engineering Congress and Exposition. New York City, New York, United States: American Society of Mechanical Engineers; 2014. p. V04AT04A032.

33. Faubion G, Jeffries K, Wells D. Addition of high-performance continuous steering axis further enhances accurate AFP robot; 2013. Guy Faubion. Published by Society for the Advancement of Material and Process Engineering.

34. Denkena B, Schmidt C, Weber P. Automated fibre placement head for manufacturing of innovative aerospace stiffening structures. Proc Manuf. 2016;6: 96–104.

35. Krombholz C, Perner M, Bock M, et al. Improving the production quality of the advanced automated fibre placement process by means of online path correction. In 28th Congress of the International Council of the Aeronautical Sciences, Brisbane; 2012. p. 3922–3931.

36. Krombholz C, Delisle D, Perner M. Advanced automated fibre placement. Adv Manuf Technol. 2013; XXVII:411–416.

37. Subramanian GH, Zarnich GE. An examination of some software development effort and productivity determinants in ICASE tool projects. J Manage Inf Syst. 1996;12:143–160.

38. Hallander P, Akermo M, Mattei C, et al. An experimental study of mechanisms behind wrinkle development during forming of composite laminates. Compos A Appl Sci Manuf. 2013;50:54–64.
39. Croft K, Lessard L, Pasini D, et al. Experimental study of the effect of automated fibre placement induced defects on performance of composite laminates. Compos A Appl Sci Manuf. 2011;42:484–491.

40. Rosen DW. Research supporting principles for design for additive manufacturing: this paper provides a comprehensive review on current design principles and strategies for AM. Virtual Phys Prototyping. 2014;9:225–232.

41. Velu R, Singamneni S. Selective laser sintering of polymer biocomposites based on polymethyl methacrylate. J Mater Res. 2014;29:1883–1892.

42. Tymrak BM, Kreiger M, Pearce JM. Mechanical properties of components fabricated with open-source 3-D printers under realistic environmental conditions. Mater Des. 2014;58:242–246.

43. Jayakumar A, Ramos M, Al-Jumaily A. A novel 3D printing technique to synthesise gas diffusion layer for PEM fuel cell application. In ASME 2016 International Mechanical Engineering Congress and Exposition. American Society of Mechanical Engineers; 2016. p. V06BT08A021.

44. Mallick PK. Fibre-reinforced composites: materials, manufacturing, and design. Boca Raton, Florida, United States: CRC press; 2007.

45. Nikzad M, Masood SH, Sbarski I, et al. Thermo-mechanical properties of a metal-filled polymer composite for fused deposition modelling applications. In Proceedings of the 5th Australasian Congress on Applied Mechanics. Australia: Engineers Australia; 2007. p. 319.

46. Conner BP, Manogharan GP, Martof AN, et al. Making sense of 3-D printing: creating a map of additive manufacturing products and services. Addit Manuf. 2014;1:64–76.

47. N. Turner B, Strong R, A. Gold S. A review of melt extrusion additive manufacturing processes: I. Process design and modeling. Rapid Prototyping J. 2014;20:192–204.

48. Velu R, Singamneni S. Evaluation of the influences of process parameters while selective laser sintering PMMA powders. Proc Inst Mech Eng Part C. 2015;229:603–613.

49. Gaytan SM, Cadena MA, Karim H, et al. Fabrication of barium titanate by binder jetting additive manufacturing technology. Ceram Int. 2015;41:6610–6619.

50. Carroll BE, Palmer TA, Beece AM. Anisotropic tensile behavior of Ti–6Al–4V components fabricated with directed energy deposition additive manufacturing. Acta Mater. 2015;87:309–320.

51. Chua CK, Chou SM, Wong TS. A study of the state-of-the-art rapid prototyping technologies. Int J Adv Manuf Technol. 1998;14:146–152.

52. Zhao Z, Luc Z. Adaptive direct slicing of the solid model for rapid prototyping. Int J Prod Res. 2000;38:69–83.

53. Golnabi H, Asadpour A. Design and application of industrial machine vision systems. Robot Comput Integrated Manuf. 2007;23:630–637.

54. Keating S, Osman N. Compound fabrication: a multi-functional robotic platform for digital design and fabrication. Robot Comput Integrated Manuf. 2013;29:439–448.

55. Singh R, Singh S, Singh IP, et al. Investigation for surface finish improvement of FDM parts by vapor smoothing process. Compos B Eng. 2017;111:228–234.

56. Singamneni S, Roychoudhury A, Diegel O, et al. Modeling and evaluation of curved layer fused deposition. J Mater Process Technol. 2012;212:27–35.

57. Park SI, Rosen DW, Choi SK, et al. Effective mechanical properties of lattice material fabricated by material extrusion additive manufacturing. Addit Manuf. 2014;1:12–23.

58. Rodríguez JF, Thomas JP, Renaud JE. Mechanical behavior of acrylonitrile butadiene styrene (ABS) fused deposition materials. Experimental investigation. Rapid Prototyping J. 2001;7:148–158.