Solid Freeform Fabrication 2018: Proceedings of the 29th Annual International
Solid Freeform Fabrication Symposium – An Additive Manufacturing Conference

DESIGN AND ROBOTIC FABRICATION OF 3D PRINTED MOULDS FOR COMPOSITES

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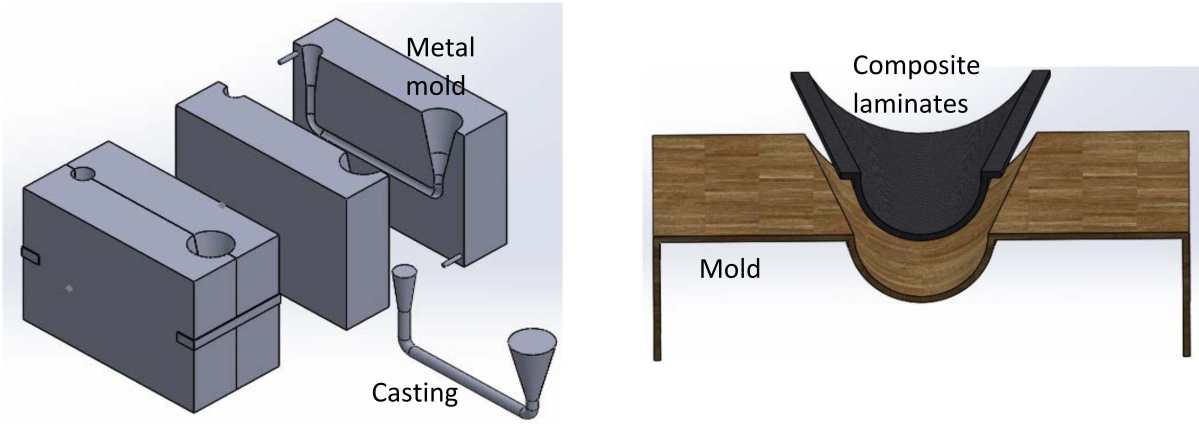
Abstract

3D printing technologies have a direct impact on manufacturing the composite structures and in particularly fabrication of molds. Molds produced through additive manufacturing methods would greatly improve product features. The material selection and process conditions involved for producing mold tooling, mainly towards Automated fiber placement (AFP) work cells. In this study, the main objective is to improve the design and fabrication of composite parts through complex molds as well as to assess and improve the production workflow through the development of an effective design environment for the existing fiber placement operation. A robotic arm will be used to hold the print surface and to follow a pre-programmed print path with a stationary extruder to fabricate the mold tooling. This paper will present a review on the selection process for mold materials and the initial experimental work carried out to investigate required properties of 3D printed molds.

Introduction

Molds are fabricated using composites also known as tools, which is plausible to virtually fabricate for any materials. The molds are in the form of blocks or series of blocks or tailored into required shape for fabrication process. The fabrication involved in different methods such as casting or pliable raw material using rigid frame or mold called lamination method as shown in figure 1 respectively. In the casting method the materials are melted in to liquid form and poured into the mold for curing to form a required shape as solid state [1]. In the lamination method the prepreg sheets and fiber reinforced composite materials are laminated on the mold material to form a required shape [2&3]. This is a form that mimics the final shape of the part, whereas the part is constructed over its outer surface which also called as positive mold. The positive type of mold is quiet rapid fabrication process relatively. The molding techniques are classified in to different procedures based on specific purpose and materials. The noteworthy techniques are vacuum forming, blow forming, compression molding, injection molding and laminating [4-8]. In this current study focused the mold fabrication for prepreg lamination techniques.



(a) Casting method (b) Laminate method

Figure 1 Fabrication of parts or laminates using distinct types of molds

Further the composite tools can classify in to two types such as hard tooling and soft tooling, which is based on type of material and process used. Ceramic and metal tools are usually used as hard tools and these materials can withstand thousands of production cycles for same set of design [9]. Also, there are excessive cost and performance tool material such as steel alloys called by Invar and it requires regular services with a specialist. When comes to soft tooling, they are quite easy to fabricate, because of fabricating with the materials like those composite manufacturers will use for the part. Subsequently, a significant key factor with tooling for composites is the phenomenon of coefficient of thermal expansion (CTE) [10]. In general, the most common materials choices for composite tools are steel and aluminum due to low cost and high-performance, but they mismatch with composites CTE. Thus, affects the quality of the dimension stability of final composite structures. If the materials like metal alloys such as Invar are close to composite CTE, which increase the dimensional accuracy during cure because the shrinkage and thermal expansion of the tool and part will be similar. Subsequently the other most common molds are made of rubber or other flexible materials, whereas most casts are made of rigid-setting materials, although this is not always the case [11]. Some materials can be used for both molds and casts and are available in a variety of flexibility and firmness properties. Among the most commonly used mold materials are liquid latex, silicone rummer, urethane rubber, and alginates. Common cast making materials include Plaster-of-Paris and Gypsum cement, concrete, plastics (resins and epoxies), waxes, metals [12 &13]

However apart from selection of materials, the fabrication of the mold will be one of the most important key factors among the physical properties of the mold, cost of fabrication and duration to construct the mold [14]. Further, the number of parts to be made with a mold, mold service life, the final product specifications, tolerance and surface finish also the noteworthy factors for fabricating the molds as shown in figure 2. There are different techniques or machining process to fabricate the mold which all based on the specific products. As mentioned earlier, in this study focuses on mold fabrication for prepreg composite structures. The prepreg layup on substrate or mold are classified into two types they are Automated tape placement (ATP) [15] and Automated fiber placement (AFP) [16&17]. Both the processes are involved similar functions; however, each method is used for different specific structure of fabrications based on mechanical strength or stiffness needed. These processes apply resin-impregnated continuous fiber. Among these techniques AFP process has unique features and automatically places multiple individual preimpregnated tows onto a mandrel at high speed., using a numerically controlled placement head to dispense, clamp, cut and restart each tow during placement. Minimum cut length (the shortest tow length a machine can lay down) is the essential ply-shape determinant [18]. The fibre placement head can be attached to an existing gantry system, retrofitted to a filament winding machine or delivered as a turnkey custom system.

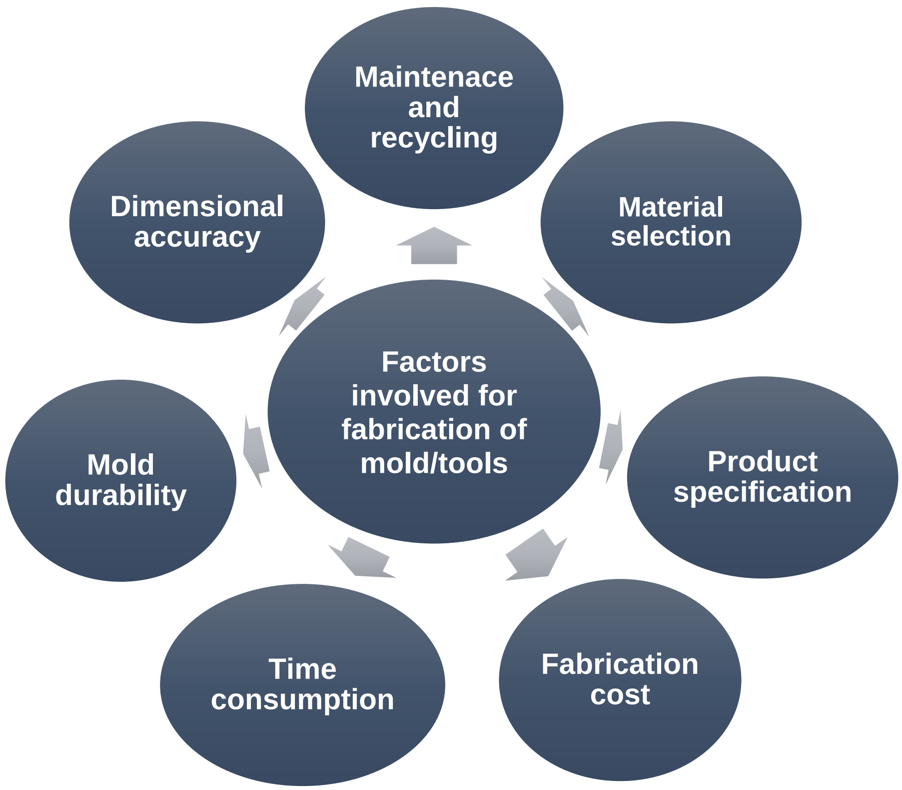


Figure 2 Factors involved for fabrication of mold/tools

AFP process achieves high production rate, better quality, efficient and low cost of manufacturing of large scale composite structures. When integrating AFP process with the robots, leads to highly automated process, further reduction in material wastage, good processing quality and repeatability. Also, the product outcome from AFP process has significant dependency on mold material property and surface. The conventional mold making process for AFP techniques are CNC machining and hand crafting. Both methods are used in all industries, for small fabrication parts handmade tools are more prevalent whereas no need of complicated CNC processing [19]. In general, the handmade mold is fabricated similarly like composite part itself, by layering resin – impregnated fabrics on top of a master model, curing the mold and removing the master to produce the cavity. This process involves labor intensive process requiring skilled workers, and to meet the required mold design specification, will undergo for various iterations which leads to substantial time consuming. Correspondingly, the mold tools fabricated on CNC machining has certain limitations like significant labour and machining, leading to excessive costs, significant material waste, and long lead times. The materials mostly used for machining process are metallic materials (aluminium, steel, or Invar alloys) [20], although non-metallic materials are also frequently used, including specialized fibre-reinforced polymer (FRP) materials, high-temperature tooling board, and others [21]. The use of metal or other hard tooling drives the need for highly complex, collapsible designs. Inflatable bladders require investment in additional tooling, adding cost and time, and are limited in the geometries.

To overcome the aforementioned limitations using conventional fabrication of mold such as CNC or handmade crafting, the manufacturing industries propelled towards Additive manufacturing or 3D printing techniques for fabricating molds or substrate which is also called by Rapid Tooling (RT) [22 &23]. This method incorporates methods of fabricating the objects by building through additional of materials, significantly opposing subtractive methods such as CNC machining, which remove materials until achieving a final shape. Fabrication of composite structures is the most original forms of additive manufacturing techniques. There are distinct types of lay-up process involved for fabricating composite structures are distinctly additive in nature, building layer by layer to form final parts. These advantages of additive manufacturing have been revolutionized with the advent of the 3D printing industry [24]. Thus, the reason the manufacturing industry propelled towards 3D printing techniques due to more pressure on global competition. The significant advantages of the 3D printing techniques for fabrication of molds towards conventional techniques are low cost, complicated design possibilities, reduction in material wastage where in CNC operation involves milling, or sanding requirements, automated manufacturing, ability to recycle waste material, minimal inventory risk, improvement in capital management, ability to easily share designs and outsource manufacturing, speed and ease of designing and modifying products as shown in figure 3.

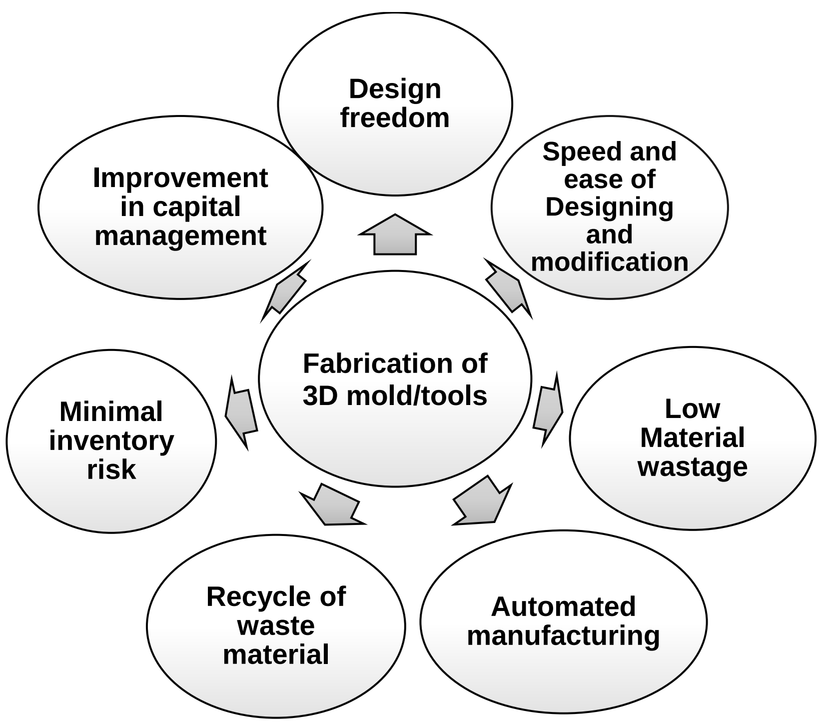


Figure 3 Advantages of 3D printed mold fabrication

There are different varieties of Additive manufacturing technologies and they all have some potential relevance for manufacturing the composite structures [25], however, in this study focused on extrusion-based technologies, as it is current relevance and a clear path to significant future impact as well [26]. The extrusion-based technology also known as Fused Deposition modelling patented by Stratasys [27]. In this method the parts build layer-by-layer by heating and extruding thermoplastic materials in an optimized controlled parameter. In general, the FDM system that are applied in industry or research sectors are equipped with three linear motion axes in order to move the process-specific tool head relatively to build-up platform in a translational motion. Based on the CAD model, a slicing program segments the geometry and plans the process paths for each slice. While slicing and modelling strategy plans planar, parallel layers that are aligned horizontally and that leads to supporting structures for geometry overhangs depending on the determined build-up direction. To break through this modelling paradigm, a multi-axis kinematic to guide the process which is called as robot-based extrusion method [28]. Integrating the additive manufacturing design freedom method and the multi-axis control or industrial robotics are further step towards development in the 3D printing revolution. The complex design fabrication can be achieved, fiber alignment can be manipulated and controlled degree also reliable when adding multi-axis motion platforms. The X-Y gantry system has limitations on complex structure lay-up, transfer molding, filament winding and automation. The robot-based 3D printed mold has unique features like potential on fabricating light weight structures, freedom on degrees of geometric complexity, part consolidation and design optimization.

Rieger et al [29] studied and investigated the application concept of additive manufactured dies to support the robot-based incremental sheet metal forming process (Robot-forming) to produce sheet metal components in small batch sizes. The result proved that AM modelled dies can indeed stabilize the sheet to reduce the deformation during the forming process compared to conventional incremental sheet forming. Viridis3D commercialized the first robotic 3D printer, the RAM 123 and achieved patent on four-axis ABB IRB460 robot to create sand molds and cores for casting metal parts. The robot is equipped with as powdered material feeder that distributes the sand and a print head that dispenses the liquid binder into the sand. Spreading sand and dispensing binder intermittently, the robotic 3D printer builds the mold layer by layer. The molds are built on a stationary table. The tabletop is a pallet that can be used to move parts on and off the machine with a forklift. the main advantage is they can quote parts with a short lead time. Molds and cores with complicated shapes can be made without a lot of tooling. Going digital is also easier. Viridis3D customer Trident Alloys sees the future in this robotic additive manufacturing system. The foregoing literature review and discussion clearly indicate that 3D printed mold break throughs with significant advantage. Significantly, it becomes important to establish the design and development of robotic 3D printed molds, whereas the research gap identified is the development of 3D printed mold for AFP process is not yet been studied or investigated systematically so far. This paper presents a robotic additive manufacturing process for mold fabrication and introducing the integration of AM and AFP process. Which pushes one step further in the direction of optimizing complex part design and manufacturing with building parameters in consideration of robotic AM and AFP process.

Methodology or statement of work

The research is structured into four components such as design of composite parts, Toolpath planning and workcell setup as shown in figure 4. The design of composite components is iterative in nature and requires numerous steps and tools. Succinctly, it covers geometric design, fiber distribution, structural analysis and structure and form optimization. These different steps require specialized software tools and designers are often converting information from tool to tool. Further in the tool path planning, the automation of the manufacturing process involves the development of processes that translate the designed part and fiber layout into manufacturing sequencing and specific machine instructions. Due to the complexity of the fabrication process, including two robotic arms with specialized end-effectors, the toolpath planning requires careful coordination, motion and collision simulation. The research developed with the required systems to optimize and streamline the toolpath planning process. In this way, the fiber placement process becomes a part, or option, in a more ambitious production line that includes additive manufacturing and subtractive manufacturing processes. The end-goal is to have an operative cell capable of producing functional, high performance composite parts. Numerous industries take advantage of the high mechanical performance, low-weight of composites. Aeronautics leads the research with requirements for expensive, low volume, high-performance parts. However, as the accessibility of composite parts grows, the market can expand. This fourth theme of the research will focus on how to expand the use of composites in existing and alternative markets as lower design and manufacturing barriers can provide composites with an edge. Preliminarily, we are looking at high performance, medium size parts (between 20 and 100cm long, three dimensional parts) such as UAV, electronic chassis, furniture, and architectural connectors, among others.

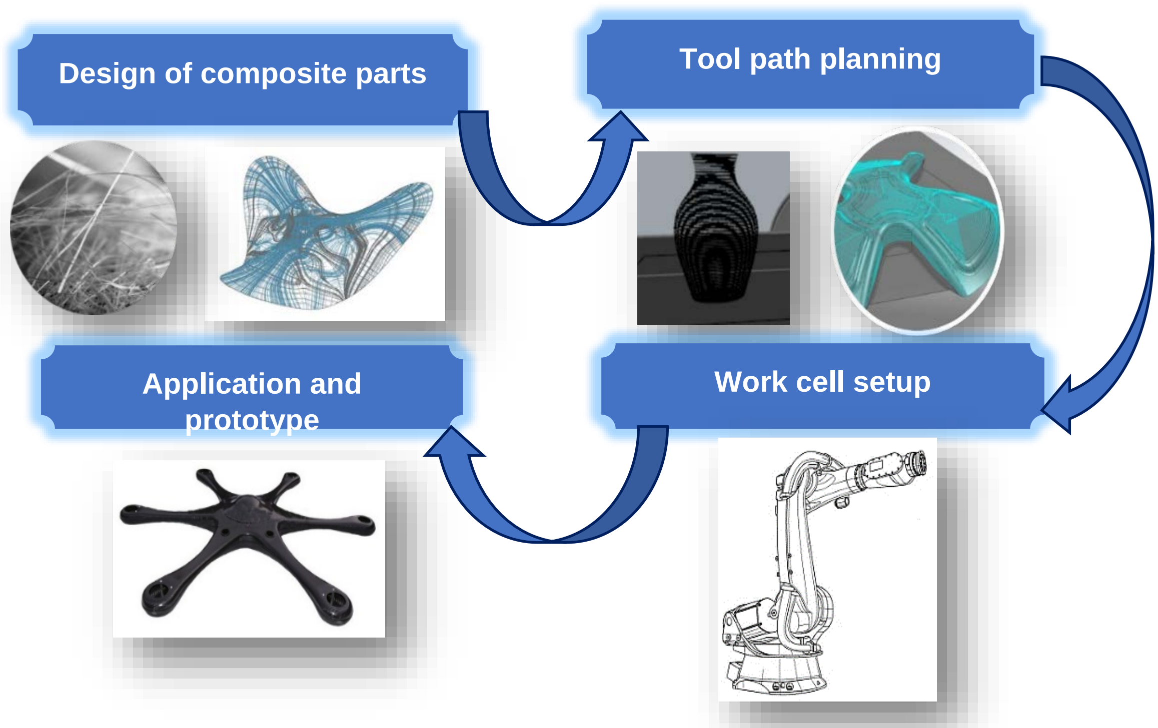


Figure 4 Process flow of manufacturing process

Novel approach and AM Robust work cell design

The robot-based 3D composites are adopted to increase the potential and the flexibility of the manufacturing process. AM robust work cell system is proposed to produce geometric specific molds that support the AFP process for composite fabrication. The modelled mold represents the negative form of the target geometry. In the AFP process, the AFP layup tool head forms the prepreg tape towards the mold shape in order to ensure the accurate position of the prepreg sheet. Figure 5 shows the bird view of our new concept work cell layout, to produce process- and geometry-specific mold sequentially to the prepreg layup process steps.

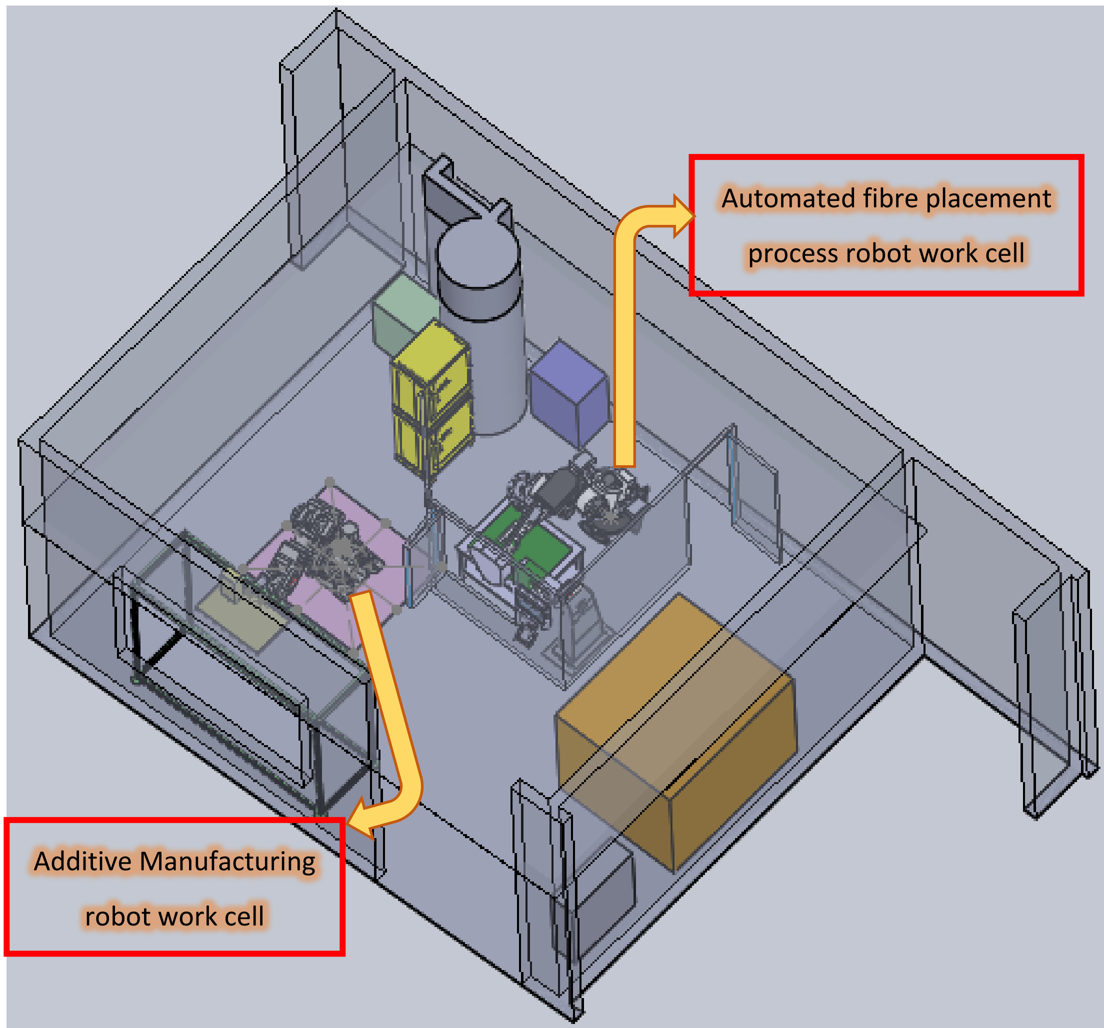


Figure 5 The bird view of our new concept robotic work cell layout using AM and AFP process techniques

The additive manufacturing robot fabricates the mold structure and the AFP robot places the prepreg tapes on the surface of the substrate. Eventually, the work flow would be continuous process like the AM robot arm will move on to AFP robot for tape placement after the substrate have been build using extruder on the work platform. The AM work cell is designed as shown in figure 6. The build platform is designed and fitted at the end of the robot arm and the extruder placed above the platform in the aluminum frame. In general, the extruder moves in X and Y direction and the build platform moves along Z direction in the FDM system, here the concept focused to fix the extruder and the robot arm fixed with build platform will move in all direction with respect to the part design. Because, once the mold is produced the arm will move onto AFP side for prepreg placement process. The build platform is designed and analyzed to withstand the working load. The build platform is made up of aluminum frame and wooden platform is fixed on top. Also, the heating element is also incorporated with the building platform to maintain the glass transition temperature or just below melting temperature of working polymers to achieve the better dimensional stability.

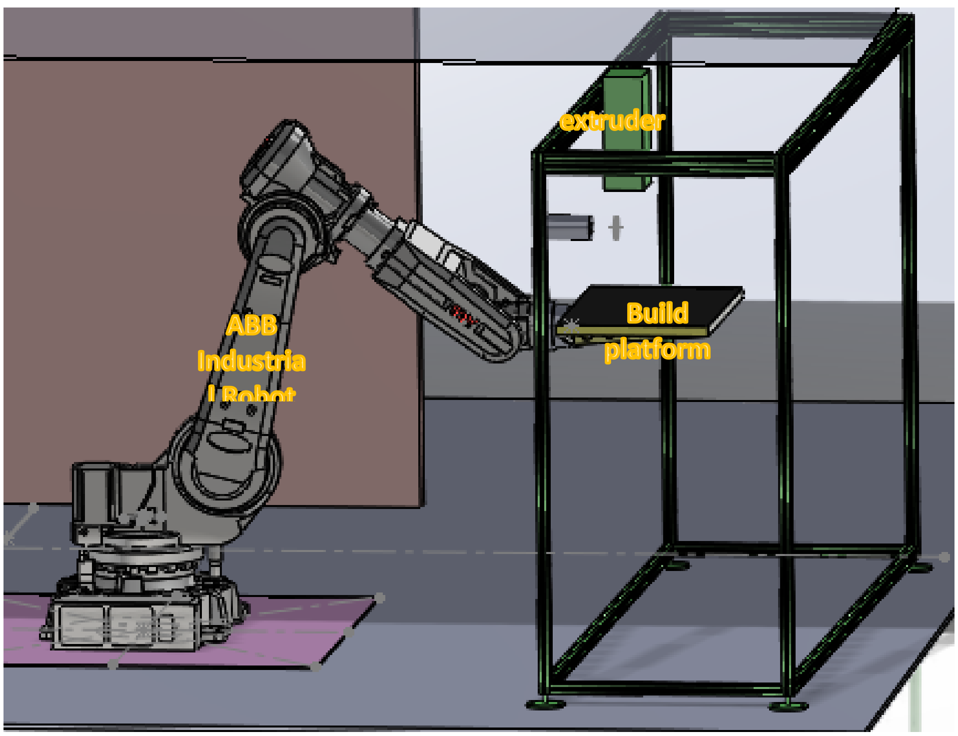


Figure 6 Additive Manufacturing robot work cell design

The concept focuses as the FDM process that melts a thermoplastic filament and extrudes a pellet to model the mold structure. The major advantage of the robot-based approach is the possibility to produce geometry-specific mold adapted to the target shapes at different forming stages. The process chain to produce is digitally defined and no geometry-specific tool is required. Also, the robot manufacturing method makes the possibility to realize the modelling process in free determinable directions.

Initial experiments

The evaluation of the processing parameters is divided into two segments. They are AM and AFP process. Though initially the research begins with AM process alone to test the additive manufacturing mold with varied sizes. Therefore, the initial design parts are produced by means of AM robot system as shown in figure 7, since the described robot-based FDM process, and the tool path are generated based on the shape of the mold part structure. The initial experimental validation for the extrusion process is performed on AM robot. The experimental work influences the robot moving speed, extruder diameter and melting temperature. After certain trials, robot constantly moves at a speed of 7mm/min. all experiments are performed with 3mm of nozzle diameter with PLA and ABS material. The working temperature adjusted based on the material used during printing. In general ABS material has exemplary thermoplastic characteristics, which is used to transfer the results to the group of thermoplastic extrusion materials.

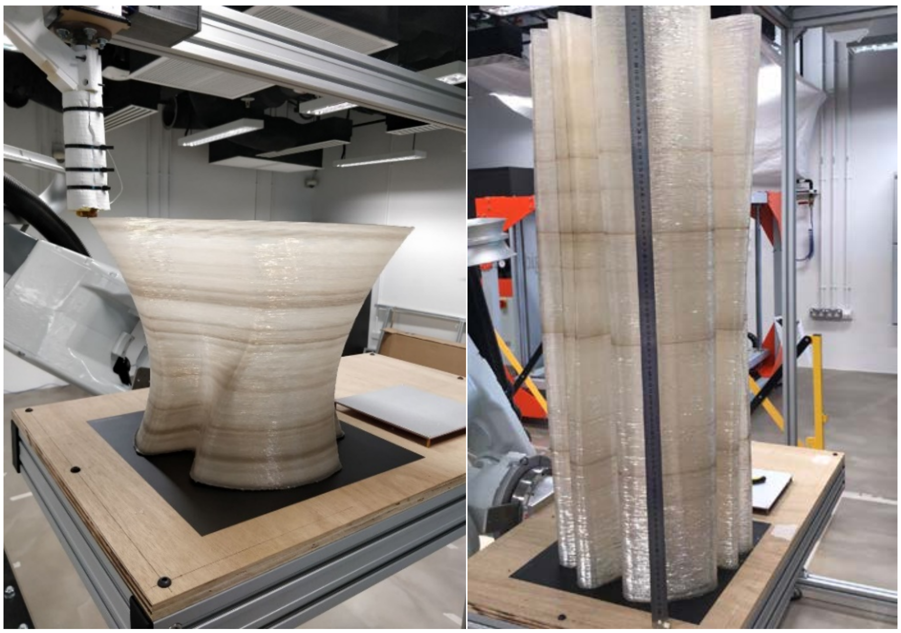


Figure 7 Test specimen produced using AM robot system

Conclusion and Future work

As described above, this paper initially overviews the need of mold fabrication technology and converging into the additive manufacturing technology roles in fabricating the mold for Automated fiber placement process. Which briefly describes the conventional fabrication method and its limitations. Then introduces robotic additive manufacturing concept and its requirements in the advanced manufacturing method. Based on this new novel approach AM robot system, the initial trials evidence the general feasibility and the potential of mold modelling using robot-based extrusion process. The initial experiments have shown that AM modelled mold can indeed stabilize the prepreg sheets while fabrication. From the above description and discussion, the conclusions and future works are: Robotic additive manufacturing has a unique advantage in complex geometry printing and large-scale manufacturing. It can be simulated in an industrial robot simulation and offline programming software platform. The future work is to model complex geometry modelling mold to fabricate the composite structures. In addition to develop the system that uses the process simulation as a tool in AM part design and optimization with respect to the mechanical, thermal and electrical property requirements. To develop the large structures mainly focusing on aerospace and medical applications.

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