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Application of robotic manipulation for carbon fiber reinforced polymers manufacturing- A survey

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ABSTRACT

With the rapid advancement in the manufacturing industry, there has been a massive rise in the demand for products made of fiber reinforced polymer composites as they have high stiffness and strength to weight ratios. They are widely used in the manufacturing of parts in aerospace and automobile industry. The manual draping process of prepreg on the mold is time intensive and requires a highly skilled worker to perform the task. Various techniques have been designed to automate the process of composite parts manufacturing using automated fiber placement (AFP), automated tape laying (ATL) and automated plies layup. These methods use robots equipped with an end effector designed to drape the prepreg. The system utilizes both single and multi-robot cells for the process of composites manufacturing. The aim of this paper is to review the techniques and strategies employed for conforming and grasping of prepreg. The paper will also delve into the process parameters that influence the composites manufacturing process and investigate the impact of correct and inaccurate selection of process parameters on the final product. The paper will also discuss the limitations, challenges and future prospects for automated composite part manufacturing.

1. Introduction

Fiber reinforced composites have been extensively used in the manufacturing industry owing to their high stiffness, strengths [1,2] and low weights [3] . There are various types of composite materials available in the market such as, glass fiber reinforced polymer [4], aramid fiber reinforced polymer (AFRP) [5] and carbon fiber reinforced polymer (CFRP) [6]. Even though the market's rise was hindered by Covid-19, it is expected to rise up to $112 billion by the end of 2027 resulting in a compound annual growth rate (CAGR) of 6.88 % [7].

The manual process involves a skilled worker draping the fiber ply on the surface of mold and applying compaction force on the ply with the help of hand or different tools such that the mold and ply stick together without any wrinkles or air pockets [8]. The process is repeated till the number of piles required for the manufacturing of a part are stacked together. Fig. 1 shows the block diagram of the general steps involved in composite part manufacturing.

This process of manual lamination is time consuming and tedious. For this reason, a lot of effort has been put in by researchers to develop both automated Fiber Placement (AFP) and Automated Tape Laying (ATL) techniques which involve the use of a robotic arm for developing carbon fiber composite parts. An alternate approach of manufacturing carbon fiber product is to mimic the hand layup process using single or multi-robot systems. The process involves the use of multiple robots, where one robot is responsible for draping the prepreg by applying the desired compaction force on the mold while other single or multiple robot manipulators are used to maintain tension in the prepreg to ensure proper layup. These methods have shown great promise in enhancing the manufacturing process of composite parts. Fig. 2 depicts the process of prepreg draping on mold's surface. Prepreg sheet is conformed onto the mold using a roller. A heat source is attached to the robot to enhance the adhesive properties of the resin and grasping robots is used to maintain the required tension in the prepreg. F_c is the compaction force of the roller, F_N is the normal force and F_T is the tension created by the grasping robot.

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1.1. Related studies

There have been some survey studies aimed at providing comprehensive insights into the recent advancements, challenges and trends within composite parts manufacturing. Björnsson et al. [9] did a comprehensive review on grasping strategies for draping prepreg sheets. Another study focused on the comparison of different path planning algorithms used in AFP for developing layup strategies [10]. Different types of defects inspection techniques were discussed in [11,12]. Elkington's study focused on the progress and challenges associated with automated plies layup [13]. Newell et al. [14] provide an overview of the advantages of automating the prepreg broadgoods manufacturing process to improve repeatability, quality, and consistency, with a current focus on cutting systems for profile production. Hassan [11] reviews the manufacturing defects and performance of complex shapes and prepreg based composites. Defects are discussed in four different parts; complex shape manufacturing, prepreg manufacturing, vacuum bagging and curing process. In complex shape manufacturing three main defects are pointed out, thickness and non-uniformity especially in the corner thickness, non-uniform resin distribution and inter laminar defects including void and fiber wrinkling. Manufacturing defects in prepreg manufacturing includes layup process defects, these defects are thickness uniformity, resin distribution and fiber wrinkling. Vacuum bagging process includes thickness uniformity, resin distribution and void content. The defects related to curing process such as, thickness uniformity, resin distribution and inter-laminar voids are also discussed.

1.2. Automated fiber placement

A gantry [15,16] or robotic system [17,18,19] with a fiber placement head attached to it makes up the AFP system. The AFP head makes it possible to lay down several carbon fiber composite material tows on a mold's surface. By implementing the proper process parameters, such as heating, compaction, and maintaining tension in the ply, satisfactory bonding between the substrate is made certain [8]. A laminate is made up of several tows, which are subsequently bonded to produce a laminate from a succession of tows. According to [20], The whole procedure of AFP comprises of four distinct segments, which include: Design, Process Planning, Manufacturing, and Inspection. Large-scale composite structure fabrication prior to the development of AFP technologies was mostly carried out using ATL and filament winding. The idea of employing tows rather than tapes was first formally described in 1974 [21]. AFP precisely places continuous fibers on the surface with fast deposition rates, thus making it suitable for parts with complex shapes [22].

1.3. Automated tape laying

Among the most renowned automated manufacturing processes for carbon fiber composites is automated tape laying (ATL) [23,24,25,26]. The ATL carbon composites manufacturing method can be employed with large fibers compared to the AFP. ATL is suitable for slightly curved surfaces since the unidirectional tapes used are wider than in the fiber placement process. The width of UD tapes is of different sizes. For near flat surfaces, tapes with a width of 300 mm can be used and for intricate shapes tapes with narrower tapes are utilized [27].

1.4. Automated plies layup

Automated plies layup method is used for draping prepreg sheets on the mold using articulated robots [28]. In this method, multiple robots are utilized for draping and gripping. The robot responsible for draping mimics the hand layup process of prepreg sheets. Robotic placement of plies, finishing, sheet lamination-based additive manufacturing, and assembling are just a few of the practical application areas where robots or essentially collaborative robots (Cobots) designed to work alongside humans are being used [29,30]. The handling of flexible plies necessitates coordinated movement and control of multiple distinct robots [31]. Robotic cells are generally used for woven prepreg sheets but such cells have also been used to drape unidirectional fibers [32]. This study is focused on the recent works that have been carried out to automate the layup process for carbon fiber composites manufacturing and it will also provide insights on the notable ones and their defects or limitations. The paper focuses on methods involving prepreg, but it will be explicitly mentioned when dry fiber is being handled.

2. Robotic manipulators for handling and conforming

To carry out prepreg conforming process, a robot manipulator should have adequate payload capacity to withstand the weight of prepreg and the conforming end effectors. It must have high precision to ensure the prepreg is conformed at the desired location. Its dexterous workspace should entirely cover the mold. For semi-autonomous systems, the robot should have safety sensors to avoid injuring the human. Based on the mentioned features, multiple robot manipulators have been deployed in the composites manufacturing industry. KUKA KR360 for draping fiber plies over a mold [33], KUKA iiwa 7 is used for applying compaction force on prepreg and for holding the prepreg two robots Epson S5 and Epson C3 are used [34], Three KUKA iiwa 7 robots are used for draping and grasping [35] [28]. ABB IRB 140 6-axis robot is used with different end effector tools is used for pressing prepreg and rolling on prepreg [36]. Two KUKA iiwa R7 and one KUKA iiwa R14 are used for grasping

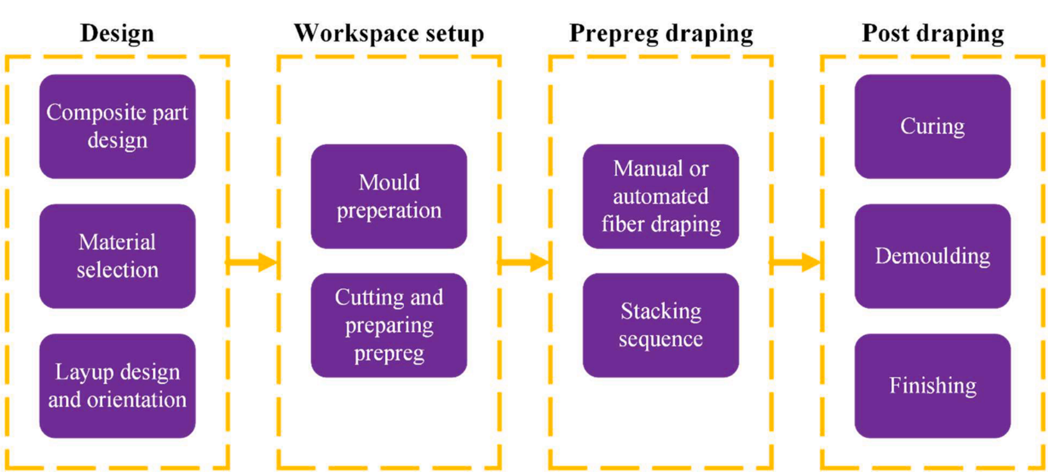

Fig. 1. Steps involved in composite part manufacturing.

and draping [37]. Compaction roller modules are used for fiber placement [38]. Table 1 shows the specifications of robotic arms that can be used for draping and grasping of prepreg.

From the data presented in Table 1 feasibility of the robot can be determined depending on the requirements of the task. The precision of all the mentioned robot manipulators is exceptional but if very high precision and repeatability is required then Epson S5, Epson C3, Dobot CR5 and Dobot CR3 can be utilized. When dealing with large composite parts, robot manipulators such as KUKA KR150 and Motoman SK120 might be suitable because of their large payload capacities and long dexterous reach. Robot manipulators such as Franka Emika Panda, KUKA iiwa series, Dobot CR series and Universal Robots UR series are collaborative robots. These robot manipulators can be beneficial where human intervention is necessary during the process. For more complex moulds, flexible robot arms can be utilized to increase dexterity [55].

3. System components

The automated system includes grasping end effectors to pick and place the ply and also generate tension and shear in the ply. Rollers of different sizes and materials are used to conform the composite prepreg layers. Heating components are attached to the robotic arms to heat the prepreg in real time to reduce the viscosity of the resin for better adhesion between layers.

3.1. Grasping mechanisms for prepreg

Grasping of prepreg sheets is a vital element in draping. End-effectors are equipped with grippers that must grip the ply during the draping process for improving the quality of the draping process by maintaining the required tension. This can also be done using dedicated structures with clamping mechanisms [56], vacuum cups handling dry fibers [57] [58], or the other active end-effectors. When working with complex shapes, such as curved surfaces or corners on the mold where the carbon fiber is being placed, it is crucial to have appropriate end-effectors. These end-effectors help ensure that the carbon fiber is positioned correctly to avoid any defects or imperfections in the final product. Malhan [59] generated online grasp plans to avoid accidental contact and maintain appropriate tension of the prepreg sheet, different grasp locations were assigned depending on the draping stage. Two Kuka iiwa 7 robots were used for grasping the prepreg. Malhan et al. [35] used KUKA iiwa robots and used a method involving state space correlation calculations in order to determine waypoints for grasping robots with respect to the mold coordinate frame. Malhan [45], they used 6 degrees of freedom (DoF) robot manipulators Epson C3 and Epson C5 for grasping. The trajectories of grasp locations for each robot are generated by an algorithm similar to CODES3 [60]. The behavior of prepreg sheets was simulated by Manyar et al. [61] using vegaFEM [62]. The shortest path from one grasp location to the next was computed using Djikstra algorithm [63].

A customized Robotiq gripper with holes for allowing compressed air to remove any tackiness between the carbon fiber ply and the gripping tool was introduced by [28] . To release the carbon fiber ply from the gripper, compressed air is blown through the valves, that pushes the ply off the gripper. The Robotiq gripper's rubber pads were replaced with PTFE to avoid prepreg from sticking to the end effector. A resistance roller based design for grasping and maintaining tension was applied by [64], which allows for better gripping of the carbon fiber plies with minimal tack. When the rollers have physical resistance due to the pneumatic pressure, the rollers stop rotating, and the grip is maintained between rollers and the ply. However, when the resistance of rollers is removed, they are free to roll, and the ply is released through their grip. Björnsson et al. [65] four different solutions were generated to pick plies from flat storage areas and stack them on flat laminate using vacuum cups. Qualitative analysis was done to inspect the results. Multi-purpose end-effector was designed and tested by Papadopoulos et al. [66] which was able to manipulate, grasp, and apply force on the plies. A multi-arm system for composite material handling was developed by Buckingham [67] Fig. 3 illustrates the grasping of prepreg sheets using vacuum cups and twin finger end-effectors. With vacuum cups prepreg sheets can be grasped from the central region but with twin finger end-effectors, the prepreg is generally grasped from the edges or corners.

3.2. Consolidation

There are two categories of rollers used in the automated prepreg conforming process. One is the hard rigid rollers, and the other is the soft conformable rollers. Fig. 4 shows the different types of materials used for manufacturing compaction rollers.

Conformable rollers are made up of either silicone or rubber. Due to their high flexibility, they can be used on intricate molds. They provide better resin flow among the prepreg stacks and are useful in removing air bubbles that arise during the process. Since these rollers are not hard, they do not leave marks on the surface of the prepreg after the force is applied. Now coming over to the drawbacks of soft rollers, they are sensitive to temperature which means that the rollers may get damaged at high temperatures. Silicone and rubber are also sensitive to chemicals, so the selection of resin is vital when dealing with these rollers. Some rubbers may have inconsistent deformation which can have adverse effect on the quality of the consolidation because of the uneven conforming force [68].

Rigid rollers are beneficial when high pressure needs to be applied. They have better chemical and temperature resistance compared to the conformable rollers. Hard rollers go through less wear and tear, making them more durable than soft rollers. Stainless steel handles the highest pressure, but hard rollers are prone to leaving air bubbles in the layers. They are not flexible which makes them not suitable for complex molds. Polyurethane and PolyTetraFluoroEthylene (PTFE) can apply force

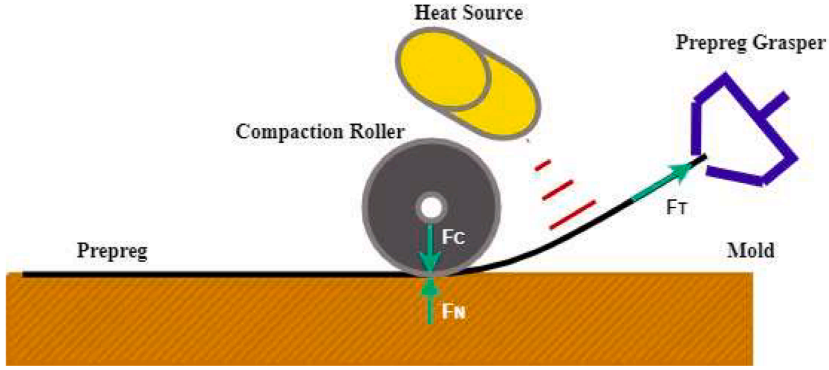

Fig. 2. Automated ply layup.

Table 1
Specifications of robot manipulators for prepreg grasping and draping.

Company/model	Application	Working radius (mm)	Payload (Kg)	Range of joint speed (°/sec)	Repeatability (mm)	Cobot	DOF
KUKA iiwa7 [39]	Grasping/ Draping	800	7	98 - 180°	±0.1	✓	7
KUKA iiwa14 [40]	Draping	820	14	75 - 135	±0.1	✓	7
ABB IRB140 [41]	Draping	810	5	200 - 450	±0.03	×	6
Universal robots UR5 [42]	Draping	850	5	180	±0.1	✓	6
Universal robots UR3 [43]	Grasping	500	3	180 - 360	±0.1	✓	6
Epson S5 [44,45]	Grasping	786	5	350 - 720	**±0.02**	×	6
Epson C3 [45] [46]	Grasping	600	3	450 - 720	**±0.02**	×	6
Yaskawa Motoman SK120 [47,48]	Draping	2573	120	110 - 250	±0.4	×	6
Franka Emika Panda [49]	Draping	855	3	150 - 180	±0.1	✓	7
Dobot CR5 [50]	Draping	900	5	180	**±0.02**	✓	6
Dobot CR3 [51]	Grasping	620	3	180	**±0.02**	✓	6
Yaskawa Motoman SDA10D [52]	Grasping/ Draping	1970	10	130 - 400	±0.1	×	**15**
KUKA KR 150 [53] [54]	Grasping/ Draping	**2700**	**150**	100–238	±0.06	×	6

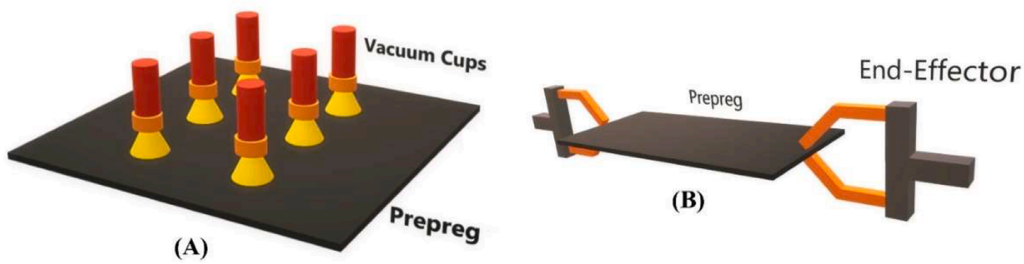

Fig. 3. (A) Prepreg grasping using vacuum grippers, (B) Prepreg grasping using twin finger mechanism.

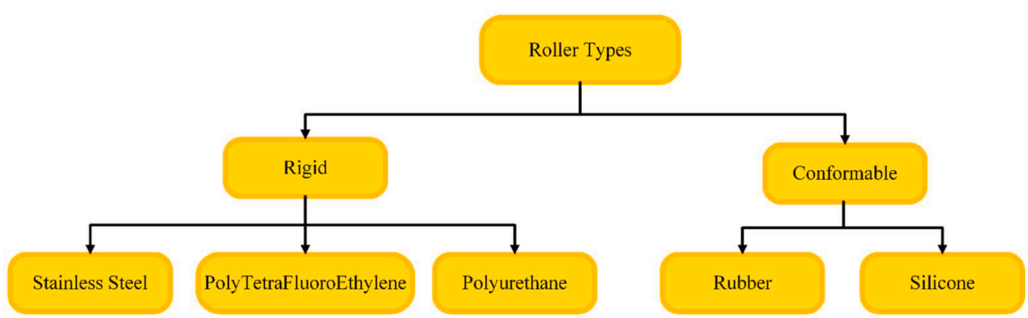

Fig. 4. Types of rollers used in automated prepreg draping.

higher than soft rollers but not more than stainless steel. PTFE has nonstick properties which does not let the resin get attached to the roller [69]. Similarly to soft rollers, resin compatibility is an issue for polyurethane rollers [38].

A flat surface is best conformed by a roller and a corner is best conformed by a dibber [70]. Profilers are used for highly contoured mold surface where compaction rollers are deemed unsuitable. Various types of end-effector tools have been developed, for example Southwest Research Institute (SwRI) [64] designed a wedge shaped compaction tool. This tool is inspired by a human hand and mimics the hand layup process to conform on complex surfaces. A dual tool end-effector was designed in with both a cylindrical and convex roller attached on the same flange of the robot [53]. A hybrid approach of robotic arm and vacuum was applied by Elkington et al. [71] to specifically avoid bridging defects on concave curvature molds. Different tools can also be integrated into a single end-effector as done by Elkington et al. [36] Robot manipulation can allow the use of appropriate tools depending on the mold's surface. Generally, however, a roller is designed and used for the draping process in AFP and ATL applications. During AFP and ATL applications, a problem of ply gaps and overlaps can occur which is resolved by ply steering techniques [72,73,74].

There are different standards that can help assess the conformability of the composite sheets. ASTM D7264/D7264M evaluates the flexural properties such as flexural stiffness and strength of the composite material [75]. The other standard is the D3039_D3039M-08 which evaluates the tensile properties of the composite material [76]. By implementing these standards, an assessment can be made on the efficiency of the consolidation force applied by the rollers.

3.3. Heating

Studies by Bakhshi et al. [34] and Engelhardt et al. [77] have shown that the most important process parameter is temperature when it comes to the draping of the carbon fiber. The optimum temperature of the prepreg produces the most refined carbon fiber product. A heat gun blows hot air onto the prepreg to raise its temperature to a certain point [45]. Another method for heating or providing the required temperature for draping process is an infrared (IR) lamp. IR lamp heating is used in CFRP layup process to achieve the necessary temperature required for the conforming of the carbon fiber prepreg [78]. Laser heating has also been used for heating prepreg tapes and they are highly efficient but at the same time are highly localized, which makes them unsuitable for large prepreg sheets [79]. Although some research has been done separately for the effect of different types of heating methods on carbon fibers, their direct comparison in case of CFRP manufacturing is scarce. Table 2 shows the comparison between IR lamp, Heat gun, and laser based heating of carbon fiber during the layup or draping process [28,36,38,45,77,80,81]. Table 2 shows the characteristics of different heating sources.

A study by Venkatesan et al. [80] used an IR lamp equipped with a 30 mm tungsten filament that could operate at variable output power. This heater was used to provide the necessary heat to the carbon fiber prepreg. The defects were minimized after the use of optimized values of IR heater output power and layup speed. Therefore, it is necessary to calibrate the heating power of the heat sources for a defect free final product. Fig. 5 illustrates the heat absorption by prepregs from different heat sources.

3.4. Vision inspection techniques

There are several defects that can occur during the process of composite layup. Fu et al. [82] discussed these defects in the manufacturing of composite materials. Resin matrix defects are discussed including residual stress both in thermosetting and thermoplastics, void defects are discussed in hot pressing, autoclave, resin transfer molding and in 3D printing, resin rich defects, fiber wrinkles, waviness defects, interfacing defects, machining defects (cutting and drilling) and lastly some non-contact defect detection techniques are discussed. These non-contact defect detection techniques are comprised of visual inspection, acoustic emission, ultrasonic testing, digital image correlation, infrared thermography and others. A laser and vision based inspection system was developed to find defects such as, deviated fiber angle and gap between tapes [83]. Malhan et al. [28] used a depth camera to monitor the carbon fiber in real-time during the layup process. The state of the carbon fiber sheet is extracted to determine the defects like wrinkles, air pockets, and voids in the carbon fiber prepreg. The inspection of the prepreg composite structure after conformation was carried out using a DinoLite AM7915MZT digital microscope. The process involved comparing undamaged areas, which served as the standard reference, with damaged area [45].

4. Process parameters in automated CFRP manufacturing

The process parameters in automated composites manufacturing play a crucial role in determining the quality, efficiency, and properties of the final composite product. Different materials, shapes and sizes of end effectors determine the layup quality. The Table 3 shows the different studies and investigations done on determining the suitable materials, the type of layup process, dimensions of custom compaction rollers, identification of optimal compaction forces, the heating techniques used for prepreg, and the layup speed. The goal of these studies is to minimize the defects that arise during the layup process. Defects like voids, wrinkles, fiber misalignment, and resin rich volumes can adversely impact the integrity of the composite part. By optimizing the process parameters (Force, temperature and layup speed), manufacturers can improve their existing production capabilities.

Table 2
Comparison of the different heating methods commonly used for prepreg heating.

Comparison of heating methods			
Parameters	**IR lamp heating**	**Heat gun heating**	**Laser heating**
Heating speed	Moderate to fast	Moderate to Fast	Fast
Heat uniformity	Uniform distribution of heat on the prepreg	Uneven distribution of heat on the prepreg surface.	Focused heating with minimal heat spread
Prepreg interaction	Depends on material absorption properties	Can cause localized overheating	Can cause localized overheating
Affect resin distribution	Does not affect resin distribution	May force resin to flow arbitrarily	Does not affect resin distribution
Initial investment	Moderate Cost	Low cost	High cost

The most important parameters of concern in automated CFRP manufacturing are temperature, compaction force, and layup speed used for the draping process. The parameter having the highest effect on the CFRP end-product quality is the temperature used for heating the carbon fiber ply during the draping process.

4.1. Temperature

The most efficient and practical process-related approach to control prepreg tack and improve the overall product quality is selective temperature modification [85]. Studies by [34] and [77] show that heating of prepreg is one of the most important parameter when it comes to good tackiness and better resulting composite part with minimal defects This is further proved by the tests conducted by Ahn et al. [86] and Hayes et al. [87]. Consequently, several experimental research have focused on prepreg tack as a relationship with temperature, with most of them indicating a strong association. The ideal temperatures for different materials and different layup techniques through testing were found by different research articles, which have been mentioned in Table 3. Evidence from each of the investigations mentioned in Table 3 suggests that for temperatures on the lower side, weak tack levels are produced by inadequate contact wetting, which causes the adhesive between both the prepreg and substrate to fail. Resin penetration in fibers gets better at temperatures on the higher side, but the epoxy matrix cannot provide as much shear resistance throughout debonding because of a temperature-dependent drop in viscosity [88]. Thus, an ideal temperature is required to reduce the defects in the final product.

4.2. Compaction force

For reduction of defects in the final product, proper bonding of the prepreg to the mold is required. For draping, a force is applied using compaction roller that is moving at a desired velocity. The compaction force or pressure exerted by the compaction roller and the time of compaction called the dwell time determines the actual contact area. The force and speed are both related to each other in terms of the actual contact area, and thus need adjusting to provide a defect free final product. Table 3 shows the draping forces found for minimal defects carbon fiber product, through testing and adjusting of the compaction force. Different materials, layup processes, and layup speeds require different values of draping force. Compaction rollers of materials that can provide high compaction pressure/force are preferred such as stainless steel. Some prepreg sheets suffer from debonding at the edges of the mold when excessive compaction force is applied [89]. The research shows that compaction force plays an important role in the CFRP manufacturing. [90,91,92] Some studies have been done on solid and perforated rollers which imply that pressure uniformity changes when perforated rollers are used [79].

4.3. Layup speed

As mentioned earlier, the layup speed and draping force work together to provide contact area necessary for good quality CFRP product. The optimized layup speed through testing for different materials is discussed in Table 3 The trend is clear from the research [93,94,95,96] that a balance between the layup speed and draping force is required to minimize the defects like debonding, wrinkling, voids etc. For slower layup speed, and high compaction force/pressure, the resulting CFRP product has low number of defects, while high speeds do not give the plies enough time to achieve the necessary tackiness with

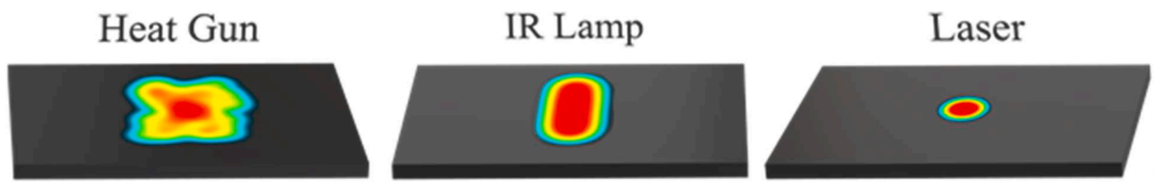

Fig. 5. Illustration of heatmaps caused by different heat sources. Area in red indicates focus region of the heat source.

Table 3
Optimized process parameters.

Ref	Carbon fiber material	Roller material	Roller dimensions (mm)	Force applied (N)	Heating type	Temperature (°C)	Layup speed (mm/s)
[45]	Aerospace grade woven carbon fiber fabric (Hexcel HexPly 913)	Silicone (Shore hardness = 30)	$d = 40$, $w = 28$, $K = 11$	10 (Flat), 20 (Double curvature) 30 (Corners) 35 (DAMAGE)	Heat gun	45	20 for $F =$ 10,20,30 40 for $F=$ 20,30 10–100 (limit) 60 (safe limit)
[36]	Woven 913 twill weave carbon material	M242 silicone	Not specified	Not specified	Nil	Nil	20 mm/s (Corners) 150 mm/s (Flat)
[28]	Carbon fiber prepreg	–	Not specified	15–30	Heat gun	45	50
[34]	6.35 mm (1/4 in) 977–2/35–12 K HTS-145 unidirectional prepreg	Polyurethane tubes	Inner $d = 20$ Outer $d = 38$ $L= 35$ Inner Aluminum (Outer $d = 22$ Inner $d = 14$ L38.8)	222.4 to 350	Nil	Nil	100–150 (straight) 50–150 (bends)
[38]	Thermoset composites (CFRP)	Solid stainless steel Soft and hard polyurethane Perforated solid slotted rubber	Not specified	350	Heat gun	200	100
[80]	Carbon fiber/polyamide-6	Steel	$w= 80$, $d= 12.7, 25.4$	Not specified	IR lamp	25–250	5.94 (optimum) 3.33 - 33
[84]	Carbon fiber/PEEK	Stainless steel	$W = 50$ $D= 3$	48–109	Laser	200	13.33

the mold's surface, and thus defects are more visible in the final product. High layup speeds also adversely affect the interply shear strength [97].

4.4. Tackiness

The fiber plies that are deposited on the mold must offer a specific amount of stickiness to the mold, known as prepreg tack. Tackiness of the prepreg sheet is dependent on temperature, layup speed and compaction force [98,99,100,101]. in order to keep carbon fiber plies in the proper location. The prepreg tack is one of the most crucial parameter to achieve a good quality composite part [102]. ASTM D8336-21 is a standard testing method to measure the adhesion of a partially cured composite prepreg to a substrate [103]. The process parameters that influence the tack of the prepreg are mentioned in the Table 4.

The process parameters in Table 4 are interrelated. If the process requires faster layup speed, then a high compaction force can be applied to compensate for the adverse effects. Higher temperatures reduce the viscosity of the resin which makes it easier to flow in the fiber matrix thus requiring a low compaction force to achieve good tackiness. Higher temperatures can partially mitigate the negative effects caused by faster layup speeds. A low layup speed increases the pressing time of the roller which results in better distribution of resin in the fibers.

Table 4
Process parameters and their impact on tackiness.

Process parameters	Good tackiness	Poor tackiness
Compaction force	**High**	**Low**
Layup speed	**Slow**	**Fast**
Temperature	**High**	**Low**

Although it is necessary for the prepreg ply to adhere to the mold, there is a risk that the resin may also adhere to the layup tool, causing the prepreg ply to stick to the tool or cause uneven resin distribution. This can generate defects such as wrinkling. Fig. 6 depicts the accumulation of resin on the surface of the roller while performing the layup process.

This sticking can cause an undesirable situation and can also make the resin distribution non-uniform. To avoid this stickiness of ply to the tools on end-effector, the following methods are recommended:

PTFE has non-stick properties which makes it a good material choice for tasks in which sticking is undesirable. It is widely used in making non-stick household utensils. However, in CFRP manufacturing, it is best used as a coating tape on the tool for avoiding stickiness of tool with the carbon fiber ply or tape [34].

Studies have also found acetone to be a good agent to remove resin from the tool. It is recommended for cleaning because acetone is a powerful cleaning agent that easily dissolves oil, waxes, resins, and other particles that might clog equipment or molds. These residues are broken down by acetone, which facilitates rapid and easy machine and mold cleanup. [36] used the acetone for cleaning the mold before giving it two coats of LoctiteTM 700-NCTM release agent for finishing. Studies by [104,105,106,107] show that acetone is useful for cleaning the tool for CFRP manufacturing. However, acetone can cause drying, cracking of skin, and irritation to eyes, throat, and nose. Therefore, proper equipment must be worn before cleaning with acetone [108].

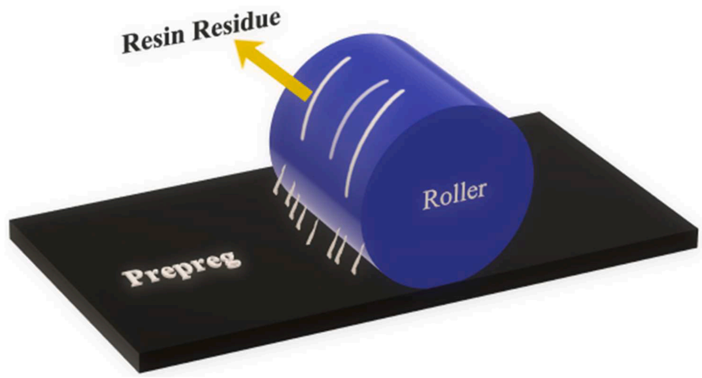

Fig. 6. Resin sticking on compaction roller.

4.5. Debulking frequency

Air pockets can occasionally be found after the draping process, but it is possible to properly eliminate these perceived flaws during vacuum debulking. Krogh et al. [109], the authors used an automatic debulking system for the purpose of measuring the effect of debulking on draped plies for defect removal. A high-fidelity 3D scanner was used to determine the defects in the ply. According to the authors, the usual result of an improper debulking is when an air pocket is not reduced causing wrinkles. Considering this, one strategy may be to cautiously reject any conformed plies that have air pockets. However, it has been observed that certain air pockets can be removed entirely. Debulking has been proven to be effective in removing air pockets [110,111,112,113,114].

In conclusion, the layup speed, draping force, temperature, roller material, prepreg material, and layup process being used are all correlated to each other and need to be optimized through proper testing to achieve a defect free CFRP product, but temperature of the carbon fiber plies is the most important parameter to control in order to minimize the number of defects that occur in the CFRP manufacturing.

5. Challenges and future trends

5.1. Challenges in robotic composites manufacturing

Robotic composites manufacturing involves different areas of research. Developing a robotic system which can manufacture composite structures requires a vast amount of knowledge. These knowledge domains may include composites, materials, robotics, and programming. Robotic composites manufacturing is still an emerging field. One major problem in robotic composites manufacturing is precision and accuracy. High accuracy is desired in placing fiber plies to the right mold position [115].

Material handling such as picking fiber plies, moving them to new place and then placing them is also a complex task as the fiber plies are delicate in nature. These plies are to be handled with care to not damage them. For this purpose, robotic manipulators need end-effectors that can hold fibers plies so that the can be conformed effectively [9].

For a robotic arm to perceive its environment and make use of its environmental knowledge different sensors are integrated. These sensors can help us monitor the quality of manufactured parts and manufacturing process. Cameras can be used for feedback of manufacturing process in which a computer vision model can be deployed to find defects in the carbon fiber parts.

Automating complex processes is the main goal of automated composites manufacturing process. Many processes involve difficult, multi-step procedures that demand thorough programming and control [116]. Continuous improvements in the underlying algorithms of the autonomous process are necessary to achieve the desired quality standard. Variation in the composites manufacturing process demands an adaptive autonomous process for the composites manufacturing.

Adaptability of the system in manufacturing processes where composite materials are manufactured in various shapes and sizes needs to be considered. These processes must accommodate numerous variations without the need of extensive changes in the program. In contrast, manufacturing of a fixed shape and size composite part requires only one time automation.

In composites manufacturing harsh chemicals and conditions occur which may turn out to be harmful for the robot equipment. Two main factors are heat and epoxy which may affect the manufacturing process. Durability and reliability under these conditions is also important.

Temperature changes throughout the composite layup process may vary and maintaining uniform temperature is required. This temperature uniformity is necessary for the draping and curing process. The task of heating the prepreg must be optimized in order to ensure that the heat is distributed uniformly [117]. These heating elements include heating mats, infrared heaters, heating coils or hot air blowers which can be controlled by the manufacturing systems through surface temperature feedback. The layout and placement of these elements must be carefully designed to prevent overheating or leaving cold spots. Real-time temperature monitoring is essential for quality control and process optimization.

5.2. Future trends

Machine learning and artificial intelligence can help improve decision making, predictive maintenance and overall efficiency of the system.

One of the latest trends in the robotic industry is the concept of digital twins. This concept can be explored in the robotic composites manufacturing industry. Researchers can simulate the manufacturing process beforehand to ensure the correct robotic path planning and motion planning. This method will help optimize the overall robotic manufacturing system, reduce development time and cost while improving reliability.

Collaborative robots have been recently introduced in the composites manufacturing industry. Coordinating multiple robots together can help achieve complex tasks efficiently. Integration of multiple robots is common nowadays and the development of multi robot systems to efficiently conform the prepregs can be beneficial for future applications. Some of the research areas that can be explored are mentioned below:

- Multi-objective optimization algorithms can be applied on process parameters to generate a set of solutions that provide the best trade-off for automated composite prepreg layup.
- Deep learning approaches have been applied for identification of defects in composite parts but they can also be used for optimizing process parameters and making real-time adjustments.

- Generative adversarial networks can be used to generate synthetic prepreg data to train robots in simulated environments.
- Adaptive learning strategies can be developed for collaborative robots to imitate the hand layup procedure of a labor and adapt to new manufacturing tasks easily.
- Collaborative task planning algorithms can be designed for safe human robot interaction during the composite draping process.

6. Concluding remarks

The study presented an overview of robot manipulators that can be used for prepreg sheet layup and the corresponding process parameters that influence the draping process. The importance of using the right end-effector during the layup process cannot be overstated. Rollers, profilers, dibbers, and even custom-designed end-effectors are examples of specialized tools for prepreg draping. The use of multiple tools in a single end-effector optimizes the time and energy consumption of the layup process. Temperature management is also critical throughout the layup process because it affects the adhesive characteristics of the material. Compaction force and layup speed are essential for defect-free final products and striking a balance between these two is critical for minimizing defects. There has been sufficient research in automated tape laying and automated fiber placement, but the use of robots for prepreg sheet draping requires further research.

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Declaration of AI and AI-assisted technologies in the writing process

During the preparation of this work the authors used ChatGPT in certain sections of the paper to improve the writing quality and rectify grammatical errors. After using ChatGPT, the authors reviewed and edited the content as needed and take full responsibility for the content of the publication.

CRediT authorship contribution statement

Wajih Ahmed Khan: Writing – original draft, Formal analysis. **Muhammad Umar Anjum:** Writing – original draft, Formal analysis. **Harris Khan:** Writing – original draft, Formal analysis. **Amir Hamza:** Writing – review & editing, Supervision, Resources, Project administration, Conceptualization. **Hamid Jabbar:** Writing – review & editing, Conceptualization. **Tayyab Zafar:** Writing – review & editing, Conceptualization. **Ali R. Ansari:** Resources. **Raheel Nawaz:** Resources.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

No data was used for the research described in the article.

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