Additive Manufacturing 48 (2021) 102458

Contents lists available at ScienceDirect

Additive Manufacturing

journal homepage: www.elsevier.com/locate/addma

Review

Consolidation of continuous fibre reinforced composites in additive processes: A review

Giacomo Struzziero [a,*], Michel Barbezat [a], Alexandros Antonios Skordos [b]

[a] *Laboratory for Mechanical Systems Engineering, Swiss Federal Laboratories for Materials Science and Technology (Empa), Überlandstrasse 129, 8600 Dübendorf, Switzerland*

[b] *School of Aerospace, Transport and Manufacturing, Cranfield University, Bedford MK43 0AL, UK*

ARTICLE INFO

Keywords:
Automated fiber placement (AFP)
3 D printing
Thermoplastic resins
Thermosetting resins
Layer by layer (LbL)

ABSTRACT

Additive manufacturing of continuous reinforced polymer is currently a focus topic in the composite manufacturing industry as it represents a viable solution to satisfy the requirements of high volume production and automation that could facilitate expanding the use of composite materials and meet sustainability goals. Nevertheless, several challenges need to be addressed to increase the quality standards to match those of parts manufactured by standard composite processing routes. Specifically, consolidation issues appear to be the determining factor which hold the technology back. The present review paper analyses current consolidation techniques utilised in additive processing of composites and identifies the most promising current and future manufacturing technologies capable of complying with stringent sustainability, quality and cost standards.

1. Introduction

The current challenges posed by climate change force society and industry to shift towards sustainable practices at an ever faster pace. Within this context, light, durable and strong materials are of interest to reduce scrap and minimise fuel consumption (i.e. aerospace and automotive sectors). Continuous Fibre Reinforced Plastics (CFRPs) possess significant advantages over other high performance materials, such as metals and alloys, including superior high specific stiffness, strength, resistance to corrosion and durability. Moreover, the anisotropic nature of composites allows efficient design and optimisation of structural performance. However, current manufacturing processes for the production of high structural performance composites (i.e. layup-autoclave, filament winding, resin transfer moulding) are not suitable for high volume applications and lack in flexibility, whilst their energy consumption and wastage are not optimal in terms of environmental sustainability standards. Typically, composite manufacturing processes involve three steps namely, lay-up/forming, impregnation/consolidation and curing/cooling resulting in a complex production chain associated with high production costs and low productivity, which eventually reduce the envelope of applications. Furthermore, traditional processes face challenges when they are applied to the manufacture of complex parts involving high curvatures, corners and transitions in thickness as well as thick components (i.e. greater than 20 mm [1]) which pose additional limitations to their potential. Research efforts on composite manufacturing have focused on strategies to reduce energy consumption, scrapped parts and maximising mechanical performances through the development of optimisation methodologies [2].

Additive Manufacturing (AM) and especially 3D printing of CFRPs comes into play with the potential to revolutionise the composite manufacturing industry by combining mould-free production of complex geometries with weight reduction, lower part count and lower wastage as well as additional design flexibility in terms of both shape and fibre orientation distribution. Furthermore, the intrinsic nature of the process has the potential to overcome issues associated with the manufacturing of thick composite components. Additive Manufacturing of CFRPs encompasses a number of processes in which the material is deposited such as Automated Fibre Placement (AFP), Automated Tape Placement (ATP), 3D Printing (3DP) and layer by layer deposition processes (LbL). AFP/ATP are technologies which have been developed in the past 30 years [3,4]. These processes have been investigated in depth and some have reached a level of maturity allowing production of composite parts with thermoplastic matrix with mechanical performance comparable to that of components produced using traditional manufacturing processes (i.e. autoclave, hot press). Nevertheless, their implementation is limited by the capital cost of equipment, relatively

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* Corresponding author.
E-mail address: giacomo.struzziero@empa.ch (G. Struzziero).

https://doi.org/10.1016/j.addma.2021.102458
Received 6 September 2021; Received in revised form 11 October 2021; Accepted 28 October 2021

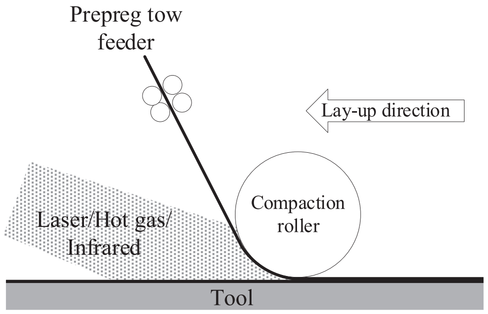

Fig. 1. Schematic representation of a standard AFT/ATP process.

low production rates and constraints in the fabrication of complex parts. Void formation and consolidation defects arise in automated lay-up due to misalignment in deposition (i.e. gaps and overlaps) and due to initial presence of voids in the prepreg material accompanied by their insufficient removal. However, the final void content of the manufactured part is a function of the subsequent steps such as melting/curing, consolidation, debulking [5] with greater void fraction occurring when in-situ consolidation strategies are implemented. Two new technologies aim at manufacturing 3D complex geometries using thermosets: 3D printing of CFRP and Layer by Layer (LbL) processing [6]. The two technologies possess the ability to combine deposition and curing in a single stage with the benefits of reducing the temperature overshoot of the component, which is a great advantage when dealing with thick and ultra-thick components. Furthermore, the flexibility of 3D printing makes it suitable also for repair applications. 3D printing, which encompasses a wide range of techniques that have reached a high level of maturity for the production of polymer and particle reinforced composites, is still at an early stage for the processing of continuous fibre composites, with the major issue of its inability to achieve high consolidation levels holding back its application despite the potential of this technology to address complex geometries and expand the application envelope of composites [7,8]. The Layer by Layer process allows incorporation of curing in the additive process, whilst applying sufficient levels of pressure. However, it currently lacks in versatility with respect to geometrical complexity.

The aim of the paper is to identify promising additive technologies, the successful application of which is linked with overcoming consolidation shortcomings. Therefore, the focus is on the state of the art of consolidation strategies applied to additive composite manufacturing processes. This is considered a critical development to make the transition of 3D printing, which currently has the greatest versatility potential, to primary structural applications as well as to simplify AFP and ATP solutions by removing post placement steps – in the spirit of the LbL process. The paper outlines the current practice and analyses the different consolidation strategies adopted. Consolidation limits when using thermoplastics material are also discussed, whilst recent trends around AM of thermosetting matrix materials are analysed.

2. Automated fibre placement (AFP) and automated tape placement (ATP)

AFP and ATP are similar technologies in which automated manufacturing of composites is carried by placing tows or tapes of unidirectional material under the action of a roller [3,9]. Fig. 1 depicts a schematic representation of a standard AFP/ATP process.

The material is laid upon a tool while heated above its melting (for thermoplastic matrix prepregs), in the vicinity of instantaneous glass transition temperature (for thermosetting matrix prepregs) or binder activation temperature (for bindered tapes). A compaction roller provides compaction for dry bindered materials and consolidation for pre-impregnated materials. The key difference between the two is the width of the material being deposited. AFP uses several narrow tapes, typically 3–6 mm wide, whilst ATP lays single tape up to 300 mm in width. The width of the tape imposes limitations in geometrical complexity. ATP machines are limited to flat or slightly curved parts, whilst AFP can deal more effectively with higher curvatures and doubly curved parts although due to the increased complexity steering of fibres might be required with the possibility of gaps and overlaps occurring. To achieve a high-quality lay-up, several parameters need to be fine-tuned, including heating power, compaction pressure and deposition speed [10–12]. Application of in-situ consolidation during tape placement can simplify the process significantly and reduce manufacturing costs [13].

2.1. *Thermoplastic resin consolidation strategies*

Thermoplastic resins are highly attractive for high end mechanical performance applications such as aerospace, due to their high fracture toughness, high damage tolerance and recyclability compared to thermosetting resins. However, due to their lack of tack and high processing temperatures, they remain difficult to use in the manufacturing of composites. Early efforts have demonstrated the feasibility of in-situ consolidation in an additive lamination process using a laser beam and a compaction roller [14]. In automated additive processing of unidirectional fibre reinforced thermoplastic materials, compaction force, temperature, laying up speed and number of passes are key parameters to achieve good levels of consolidation [4,15–17]. Typical heat sources are Hot Gas Torch (HTG), Infra-Red (IR), Laser and Flashlamp. During the process, the compaction roller is in direct contact with each layer only once; however, each layer undergoes compaction multiple times as the process evolves, which reduces significantly the level of voids in a single ply, reaching 2% after five passes [18,19]. A trade off exists between deposition speed and deposition temperature; time optimal solutions (i.e. fast deposition) may not lead to maximum bonding strength and conversely maximum bonding strength solutions lead to longer processing times [20–22] since the quality of the bond depends on the time spent at high temperature under compaction. However, bonding can also occur at sub-melting temperature [23], allowing to lower the processing temperature. The interfacial bond strength increases and void content lowers as consolidation force increases [24–26]. Additionally, the void content is reduced at lower deposition speed and for an optimal tool temperature [27–29]. A high tool temperature accompanied by slower cooling leads to higher crystallinity which positively impacts interlaminar shear strength (ILSS) [27]. Establishing a good degree of intimate contact between the incoming tape and the already deposited substrate is essential to prevent air pockets [30–34]. Utilisation of laser repasses in laser assisted ATP does not result in significant benefit on ILSS [35], but improves significantly void content and surface finish [35,36]. Crystallinity of ATP/AFP parts is found to be lower than that of autoclave manufactured parts [27,36–38], with repass treatment slightly reducing crystallinity [36]. This is explained by the fast cooling reached during ATP/AFP upon deposition and the slower evolution of temperature changes further from the heating surface. However, this is in contrast with some reports [35] in which crystallinity is found to be unaffected by repass treatment. The mode I fracture toughness of material manufactured using laser assisted ATP is 35–80% higher than that of material produced using autoclave [37,38] as a result of significant differences in plastic deformation given the difference in crystallinity between laser assisted ATP (18%) and autoclave (42%) manufactured components [38]. The ILSS benefits from higher values of crystallinity, whilst mode I fracture toughness from lower levels; therefore, a trade-off exists that needs to be considered at the design stage. The use of ultrasonic vibration as fast heat source has been proposed [39] with ultrasonic assisted AFP producing materials with a 4.6% void content [40], which is higher than the void content obtained by autoclave processing (<1%) and AFP using either laser or hot gas torch (about 3%). Ultrasonic assisted AFP produces materials

Table 1

Performance/quality achieved using AFP/ATP of thermoplastic composite. (in brackets baseline values obtained with standard processing).

Ref.	Material	Lay down speed (m/min)	Vf (%)	Voids (%)	ILSS (MPa)	Mode I Fracture toughness (J/m^2)	In-situ consolidation
[21]	CF/PEEK	6	60[a]		90 (95)		Roller/Laser
[24]	CF/PEEK	3			80 (94)	1200 (peel test)	Roller/HTG
[27]	CF/PPS	10	55	3 (1)	50 (75)		Roller/Laser
[29]	CF/PEEK	3		3 (< 1)	51 (110)	–	Roller/HTG
[35]	CF/PEEK	3	62	3–4(< 3)	43 (105)		Roller/Laser
[37]	CF/PEEK	8	60	3(< 1)	78 (112)	3900 (2900) wedge peel strength	Roller/Laser
[38]	CF/PEEK	8	60[a]			2150 (1320) (DCB)	Roller/Laser
[41]	GF/PP	0.06	61		33 (33)	1925 (1204) (DCB)	Roller/Ultrasonic

[a] prepreg Vf.

with comparable ILSS and higher mode I fracture toughness in comparison to hot pressing manufactured parts. However, optimal speeds are too low (i.e. 0.06 m/min) [41]. Multi-slice rollers [42–44] and a conformable compaction system comprising a set of three compactors [45,46] have been proposed as a means to consolidate complex geometry parts involving changes in radius and thickness; however, there are no results published using this technology. Moreover, the technological complexity might outperform the benefits.

A new process route where pre-consolidation by means of roller or ultrasonic spot welding is followed by stamp forming has also been proposed [47,48]. High quality laminates with a void content below 1% after stamp forming have been obtained [47].

Table 1 summarises the most relevant results to date with respect to consolidation strategies adopted for thermoplastic composites. Values obtained from standard manufacturing processes are listed in brackets in the cases where they are reported in the corresponding study. Without post-consolidation treatment, the achievable voidage is about 3%, which is 2% higher than in autoclave processing, ILSS is reduced by about 40% and mode I fracture toughness increase by about 35–80% compared to autoclave manufactured parts which is attributed to the significant plastic deformation. Although, the AFP technology has reached a level of maturity that allows to manufacture primary structural components, the high overhead cost of the equipment compromises the wide adoption of the process across different sectors.

2.2. Thermoset resin consolidation strategies

Thermoset consolidation strategies can be grouped into (i) in-situ consolidation by means of a compaction roller; and (ii) post-processing consolidation. To achieve good quality levels of void content (< 2%) and comparable mechanical performance (i.e. ILSS about 90 MPa) appropriate pressure together with high temperature need to be applied to the material being deposited [49–54]. The higher compliance with the contact surface make silicone rubber rollers more suitable for manufacturing of curved components compared to steel rollers; however, inconsistent deformation of the roller can lead to uneven compaction force [54].

The compaction behaviour of toughened uncured prepregs has been analysed, with different compaction limits identified for thick and thin plies [55–57]. There is a correlation between through thickness compaction and the ability of the material to flow transversally. The final level of compaction depends therefore on the thickness to width ratio. Furthermore, there is a temperature threshold beyond which compaction does not depend on temperature and viscosity [55–57]. The effect of placing a caul plate to allow better consolidation of AFP parts in autoclave has been investigated among other post-processing consolidation strategies. The caul plate application results in lower thickness variation as a result of more uniform flow during consolidation and the initial stages of curing despite the introduction of gaps and overlaps during deposition compared to when a caul plate is not used [58].

Automated Dry Fibre Placement (ADFP) is a variation of AFP which eliminates the use of prepregs and deposits dry fibres tape with binder followed by resin infusion A variation of the process using laser is named Laser-Assisted Dry Fibre Tape Placement (LDFTP) [59]. This process can handle material with a higher volume fraction by about 9% compared to conventional processing; however, the increased complexity of the infusion step due to the very low permeability of the stack of preform might diminish the benefits.

Table 2 reports the most relevant results to date with respect to consolidation strategies adopted for thermoset composites. There are few works covering AFP/ATP of thermosets. The majority of them implement post-processing strategies (i.e. autoclave, liquid infusion). Although achieving comparable results with standard processing, splitting the process in two steps moderates potential advantages in terms of automation of the process that is typical of AFP/ATP processes.

2.3. Simulation of consolidation and bonding for AFP/ATP

The use of simulation has been proposed as a means to both analyse and understand the link between inputs and outputs of AFP/ATP processing and to develop efficient process designs. To achieve the latter, few efforts coupling predictive models of the AFP/ATP process with optimisation methodologies have been used to find optimal set of parameters (i.e. deposition speed, temperature) and to minimise process time and defects such as porosity [28,60–63]. The typical assumptions of Darcy’s flow and no edge effects used in consolidation simulation of conventional composites processing routes [64–66] implying dominance of bleeding flow are not fully valid in the case AFP/ATP. In this case, squeezing flow can also occur and can affect the deformation behaviour of prepregs under compaction [56,57]. Therefore, both bleeding and squeezing flow need to be modelled to accurately predict thickness evolution and the width of the material undergoing AFP/ATP processing [67]. Consolidation parameters also determine the quality of intimate contact and consequently the strength of the interlaminar bond [33,34,68–71]. Consolidation models have been coupled with cure simulation allowing investigation of the formation and evolution of gaps

Table 2

Performance/quality achieved using AFP/ATP thermosetting composite.

Ref.	Material	Lay down speed (m/min)	Vf (%)	Voids (%)	ILSS (MPa)	Flexural strength (MPa)	Consolidation	
							In-situ	Post-processing
[52]	CF/M21	6		2	95		Roller/IR	
[58]	CF/AW194		59[a]	< 1				Caul plate+autoclave
[59]	CF/Crestapol1210	3	56		45	1100		Liquid infusion

[a] After post-processing.

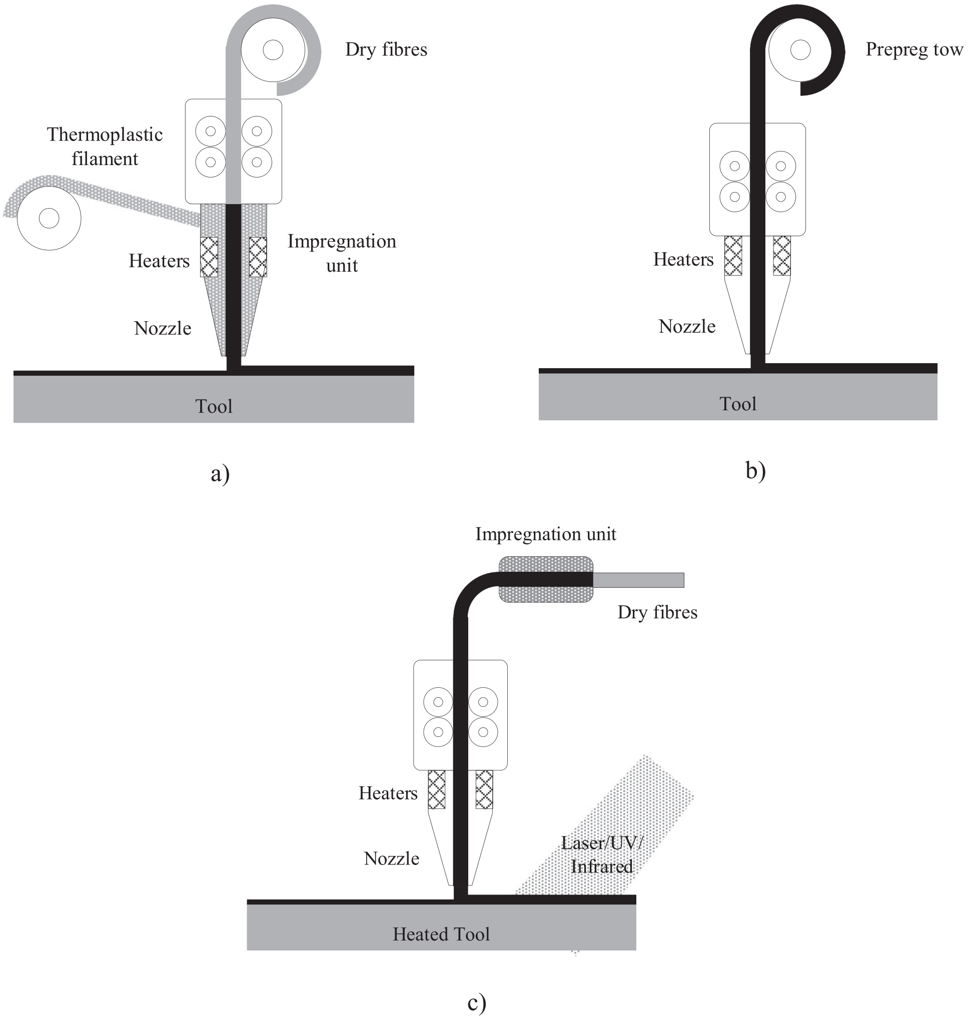

Fig. 2. Schematic representation of a standard 3D printing of continuous fibre using thermoplastic a) in-situ fusion, b) prepreg tow; and c) for thermoset.

and overlaps and the influence of consolidation and curing predicting the final thickness with 10% accuracy compared to experimental results [72,73].

3. 3D printing of continuous fibre composites

The 3D printing manufacturing process has several advantageous characteristics such as flexibility, simple use and low cost. Amongst various 3D printing strategies, Fused Deposition Modelling (FDM) has been the subject of interesting and rapid developments using different thermoplastic filaments (i.e. Polylactic Acid (PLA), Nylon, Acrylonitrile Butadiene Styrene (ABS), Polyamide (PA), Polypropylene (PP), Polycarbonate (PC)). Adding continuous fibres to FDM filaments allows achieving better performance [74]. Commercial 3D printers using continuous fibre impregnated with thermoplastic filament have been developed and patented [75,76]. Commercially available 3D printers have been used and modified by several researchers to 3D print continuous glass, carbon and Kevlar fibre thermoplastic (i.e. PLA, nylon and ABS) composites. As expected, the incorporation of continuous fibres results in significant improvements in mechanical properties compared to the unreinforced material [77–89]. Two approaches have been put forward for the incorporation of continuous fibres in printing of thermoplastic matrices: (i) in situ-fusion (Fig. 2a) which consists in merging the fibre bundle and polymer filament during the printing process [88,89] and (ii) pre-impregnated filament or prepreg, (Fig. 2 b) involving fabricating a fibre impregnated filament before used in the printing process [78,80,84]. In the case of thermosets, an impregnation unit needs to be introduced if dry fibres are used as raw material. In addition, a heating source (heated tool, laser, UV) needs to be present to cure the component in the case of thermosetting matrices (Fig. 2c).

Currently, components manufactured with 3D printing fail to meet the quality standards set by industry. There are several challenges that need to be addressed to avoid the significant drop in mechanical performance including poor wetting of dry fibre bundles which can be a source of voids, poor consolidation leading to high porosity, low volume fibre fraction and poor adhesion between layers [90]. In the following sections, consolidation strategies reported in literature to improve the mechanical performances of 3D printed components are discussed.

3.1. *Consolidation strategies of 3D printed thermoplastic composites*

3D printed thermoplastic components have lower interlaminar shear strength compared to parts manufactured with standard processing due to the inclusion of a large number of voids during manufacturing [80,89,91]. A study on carbon fibre-Nylon composites achieved 35% volume fibre fraction and voids as high as 12%, mode I fracture toughness of 118 J/m^2 and flexural strength of 546 MPa [92]. By applying subsequent compression moulding to reduce voids to 6%, mechanical performance was improved. Therefore, consolidation strategies for 3D printed components have become a focus to improve the mechanical performance of AM components. Both post-treatment and in-situ strategies have been put forward. In-situ consolidation can be provided by a

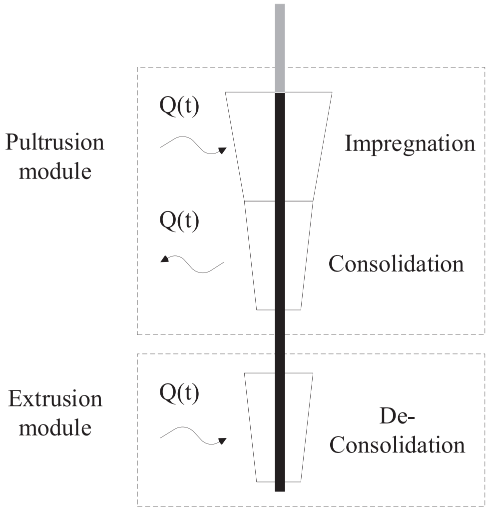

Fig. 3. Schematic representation of the CLF process.

compaction roller [93–95]. The application of pressure brings significant benefits in terms of tensile (+ 30%) and flexural (+ 45%) strength [93], since it reduces the level of voids and promotes better intimate contact between layers; however, performance is comparable with parts that have undergone post-processing in hot press only when a hot compaction roller is used [94]. In-situ consolidation has also been achieved for carbon fibres polycarbonate material right after the discharge of the material from the nozzle; the technology achieved 88% of the flexural strength of components manufactured by thermoforming which were used as benchmark and 7% porosity [96]. In-situ laser treatment is beneficial in improving bonding between layers and improving ILSS up to 35 MPa for carbon fibre/polyether ether ketone (PEEK) composites [97]. Printing in a low pressure environment has been also investigated as a means for in-situ consolidation and void reduction. A void content of 1.1%, 0.5% and 0.8% has been achieved for carbon, glass and Kevlar respectively resulting in an ILSS of 58, 48 and 32 MPa for the three types of fibre [98,99]. Recently, a 3D printer placed inside a vacuum chamber was used to manufacture carbon-PLA; the findings confirmed that porosity is reduced and flexural strength of specimens increases compared to printing in atmospheric conditions [100]. The influence of nozzle temperature has been investigated for carbon-PLA; when nozzle temperature is increased from 180 °C to 220 °C the ILSS is improved by 70% up to 25 MPa and voids are reduced from 5.5% to 3% [101]. Ultrasound excitation has been used to improve impregnation for carbon-PLA; tensile and flexural strength were found to improve by 34% and 29% respectively compared to impregnation without the application of ultrasound [102]. Post-consolidation in a hot press is beneficial in terms of void reduction and improvements in mechanical performance; however, the process involves two steps therefore diminishing some of the efficiency advantages of 3D printing [103–105].

A 3D printing process based on pultrusion has been developed to prepare a PP/E-glass filament from commingled yarn resulting in a high void content of up to 20% and significantly reduced flexural modulus by about 50% [106]. The Continuous Lattice Fabrication (CLF) process integrates pultrusion and extrusion [107,108]. In CLF, yarns are pulled through a pre-heating module in which material is partially melted. Consolidation occurs in the pultrusion module which incorporates a tapered heated die allowing the manufacture of high volume fibre fraction- greater than 50% - parts [108]. In the extrusion module, the filament is heated above melting and deposited. Fig. 3 presents a schematic representation of the CLF process.

Adding a four stage pultrusion module performing cyclic softening through consolidation-deconsolidation results in reduction of void content before deposition by more than 80% and extends the processing window in which material can be deposited with void content lower than 1% [109]. A laser assisted AM process has also been developed and used with glass fibre/PP prepregs [110]. This process outperforms FDM methods achieving parts with no voids and lap shear strength, flexural and tensile strength comparable with standard manufactured parts (see Table 3) [111,112].

Table 3 summarises the most relevant results to date with respect to consolidation strategies adopted for 3D printed thermoplastic composites. Similarly to Table 1, values in brackets refer to standard manufacturing processes where these are reported in the corresponding study. The components manufactured have inferior quality compared to standard manufactured components especially in matrix dominated properties such as ILSS due to poor adhesion within layers and poor consolidation. The 3D printing technology has interesting features such as design flexibility and low equipment cost; however, significant effort needs to be done to resolve the poor consolidation achieved. CLF processing can be considered the most promising approach to achieve consolidated components.

3.2. *Consolidation strategies of 3D printed thermosetting composites*

A limited number of works have addressed 3D printing of thermoset composites, with most not focusing on consolidation aspects. Printing speeds in the range of 0.1–1.4 m/min and filament thicknesses up to 2 mm have been investigated [113,114]. A pultrusion type system to impregnate fibres in an epoxy bath has been used entering the printing head, followed by printing and curing at high temperature producing unidirectional carbon fibre/epoxy composites with tensile strength of about 800 MPa in the fibre direction and flexural strength of 202 MPa [113]. Improved performance has been achieved by adding post-consolidation in vacuum and fresh infusion of resin to the printed part, resulting in tensile strength of 1476 MPa, flexural strength of 858 MPa and ILSS of 49 MPa which are 70%, 51% and 46% of the mechanical performance achievable with standard manufacturing [114–116]. UV curable resin has been added to preimpregnated carbon fibre achieving 7% level of porosity and a flexural strength of about 185 MPa [117].

A dynamic capillary-driven AM approach has been proposed. The new concept is based on wicking promoted by a moving heater which facilitates the resin flow between neighbouring carbon fibres. This new concept allows fast and almost simultaneous infusion and curing. The printed parts have a volume fibre fraction of 59% and tensile strength of

Table 3
Performance/quality achieved using 3D printing of thermoplastic composites (in brackets baseline values obtained with standard processing).

Reference	Material	Lay down speed (m/min)	Vf (%)	Voids (%)	ILSS (MPa)	Tensile strength (MPa)	Flexural strength (MPa)	In-situ consolidation
[94]	CF/Nylon		35[a]	3.0		1031 (800)	945 (950)	Hot Roller
[96]	CF/PC	0.35		7			615 (699)	In-situ not specified
[97]	CF/PEEK	0.12	38[a]		35 (105)		480	Roller+laser
[99]	CF/Nylon	0.5	41[a]	1.1	58			Low-pressure
[110]	GF/PP	0.25	60[b]	< 1	9 (10)	217 (140)	170 (190)	Roller

[a] Filament Vf.
[b] Prepreg Vf.

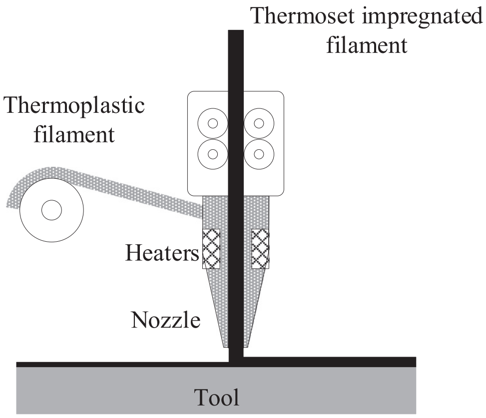

Fig. 4. Schematic representation of 3D printing of bi-matrix composites.

810 MPa [118]. A new process called Magnetic Compaction Force Assisted Additive Manufacturing (MCFA-AM) has also been put forward and applied to unidirectional carbon fibre - epoxy composites. In this concept, magnetic material, such as steel, is embedded in a rubber pad which provides consolidation to the deposited filament by application of a magnetic field. For a magnetic compaction force of 0.21 MPa, the ILSS of manufactured samples is 70.5 MPa, which is 7% less than samples manufactured using out of autoclave vacuum bag processing [119]. 3D printing using a combination of two different matrices has been carried out in the attempt to combine the benefits of thermoplastic and thermosetting matrices. In the process illustrated in Fig. 4, a prepreg filament made by thermoset resin is fed to the printing head together with a separate thermoplastic filament. The thermoset prepreg is embedded in the thermoplastic melt inside the printing head and subsequently printed. The addition of thermoplastic filament to the already impregnated carbon fibre thermosetting material lowers the volume fibre fraction down to 25–27% hindering the potential benefits of the process [120, 121].

Table 4 reports the most relevant results to date with respect to 3D printed thermosetting composites. Values in brackets follow the convention reported for Tables 1 and 4. The performance of 3D printed thermosetting components is not comparable with that of standard manufactured routes, reaching at best between 46% and 70% of what is achievable with standard processing. Therefore, additional research and investigation is needed to bring the technology to an acceptable industrial standard.

4. Layer deposition processes

A family of processes of an additive nature has been put forward based on the concept of processing full layers of the material in a sequential manner: Stepped Concurrent Curing (SCC), Layer by Layer (LbL) curing and Laminated Object Manufacturing (LOM). Fig. 5 reports a schematic describing the additive procedure in the LbL process in which compaction pressure is applied after deposition of each layer/sub-laminate.

Two variations of LOM have been proposed; one using a laser and a roller for consolidation [122] and another one using an ultrasonic roller [123]. The manufactured parts have a tensile strength and flexural strength higher than 3D printed thermoplastic parts; however, only 50–60% of the flexural strength reached by standard manufacturing is achieved. In the SCC process, [124–128] UV curing is used to manufacture GFRP. Glass fibres are more transparent than carbon fibres which helps better transmission of UV light. The maximum ILSS achieved is 23 MPa which corresponds to more than 50% reduction compared to standard manufactured parts [124,125]. The LbL process applies standard heating for curing. The LbL process achieves values of ILSS and mode I fracture toughenss equal to 60 MPa and 480 J/m^2 respectively which are comparable with the values of standard manufacture components if the pre-cure level of deposited layers is kept below a critical threshold around the gelation point [6]. The LbL technology is also capable of depositing layers of material with widths that are tens of cm, therefore allowing manufacturing of large parts.

Table 4
Performance/quality achieved using 3D printing of thermosetting composites (in brackets baseline values obtained with standard processing).

Ref.	Material	Lay down speed (m/min)	V_f (%)	Voids (%)	ILSS (MPa)	Tensile strength (MPa)	Flexural strength (MPa)
[113]	CF/E54	0.1	48			793	202
[114]	CF/EP-671	0.5	58				950
[115]	CF/E-20	0.6	48	2.5	49 (107)	1476 (2172)	858 (1703)
[117]	CF/UV curable resin	0.6		7			184

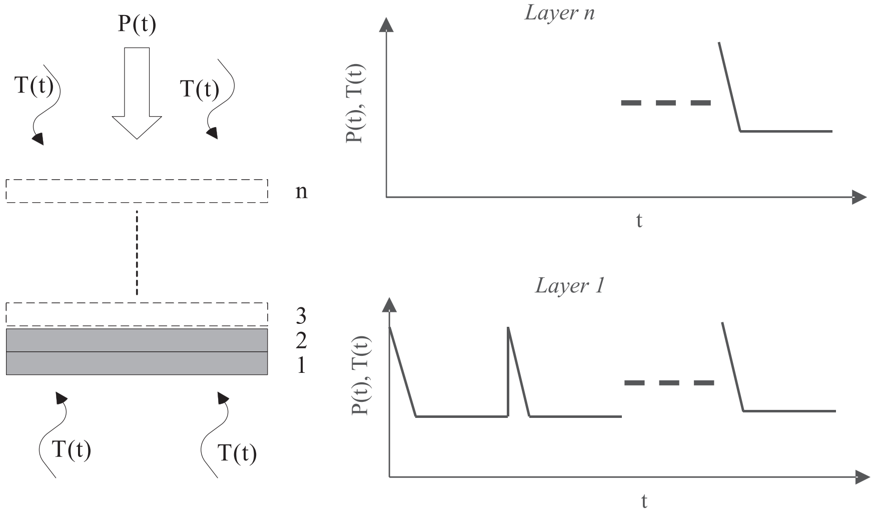

Fig. 5. Schematic representation of the LbL process and the evolution of pressure (P) and temperature (T).

Table 5
Performance/quality achieved using layer by layer processing of thermosetting composites (in brackets baseline values obtained with standard processing).

Ref.	Material	V_f (%)	ILSS (MPa)	Tensile strength (MPa)	Flexural strength (MPa)	Process
[122]	CF/PA6	49		668	598	LOM
[123]	CF/PA6	49	32	1461 (1760)	488 (1026)	UA-LOM
[124, 126]	GF/Epoxy	60	22			SCC
[6]	GF/Epoxy		60			LbL

Table 5 reports the main outcomes with respect to layer by layer deposition processes. It highlights that parts manufactured by LbL process show mechanical performance in the range of what is achievable by standard manufacturing routes. The LbL process is the most promising technology involving manufacturing of thermoset components. The process shows to be simple, effective and efficient. Furthermore, the LbL concept could be coupled with AFP/ATP equipment which could ease the overhead cost of the latter allowing its adoption across different end users.

5. Conclusions

The race towards a sustainable composite manufacturing practice passes through automation. Within this context, composite processing using additive manufacturing is a strong candidate for development in the near future. The present paper has assessed the state of the art with respect to consolidation strategies and their outcomes in terms of void content, fibre volume fraction, flexural and tensile strength, mode I fracture toughness and ILSS properties for additive manufactured composite components with continuous reinforcement.

Currently, AFP/ATP techniques can be used to manufacture high quality parts. However, the high overhead cost of the equipment together with the difficulty to manufacture high volume and constraints in terms of complex geometries limits their implementation to high-end applications. 3D printing represents a viable alternative to AFP/ATP, with major advantages around its low cost and greater manufacturing flexibility and ability to address complex geometries. However, the technology is not currently able to achieve the levels of consolidation required for high mechanical performance applications.

The curing of thermosets layer by layer (LbL) introduces a new additive manufacturing route. The technology has been proven to produce high quality parts comparable with standard processing with reduced process time. It also resolves the issue of manufacturing thick and ultra-thick thermoset components since the layers are cured and consolidated as the thickness builds up and allows deposition of layers that have width of tens of cm, whilst 3D printing and AFP processes can deposit filaments in the order of millimetres, therefore relying on deposition speed to achieve large width within reasonable process times. Nevertheless, the filament width for 3D printing could be increased by bringing more tows together in a pultrusion like fashion and the consequent design of a printing head that could deposit it. The next step is the implementation in an AFP/ATP set up for automation of the process while the same concept could be also implemented in the context of 3D printing. However, challenges with respect to in-situ consolidation are foreseen and therefore intensive investigation is required.

CRediT authorship contribution statement

Dr G. Struzziero: Conceptualisation, Writing – original draft. **Dr M. Barbezat:** Writing – review & editing, **Dr A.A. Skordos:** Conceptualisation, Writing – review & editing, Funding acquisition.

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.

Acknowledgements

This work was supported by the Laboratory for Mechanical Systems Engineering, Swiss Federal Laboratories for Materials Science and Technology (Empa) through the Empa board of directors (project code AP304-2124) and by the Engineering and Physical Sciences Research Council [grant number EP/P006701/1]; through the EPSRC Future Composites Manufacturing Research Hub.

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