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Manufacturing defects in thermoplastic composite pipes and their effect on the in-situ performance of thermoplastic composite pipes in oil and gas applications.

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Manufacturing Defects in Thermoplastic Composite Pipes and Their Effect on the in-situ Performance of Thermoplastic Composite Pipes in Oil and Gas Applications

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Abstract

Thermoplastic composite pipes (TCP) are a form of fibre reinforced thermoplastic pipes that have proven benefits such as being lightweight and non-corrosive. However, during manufacturing, certain defects are induced because of certain parameters which eventually affect TCP performance in-service. Current manufacturing techniques are challenged with on-the-spot detection as the pipe is regularly monitored. When a defect is noticed, the process stops, and action is taken. However, stopping the process is costly; hence it is vital to decrease downtime during manufacturing. Potential solutions are through process optimisation for defect reduction and an in-depth understanding of the effect of parameters that cause defect formation in the pipe. This article provides an overview of manufacturing influence on the end performance. This is intimately linked to the material features, properties, and performance in-service. The material features are the determinants for the manufacturing technique to be used. For TCP, it is a melt fusion bonding process involving heating and consolidation among other factors such as the consolidation speed and pull force. Thermal behaviour is essential at this phase as it determines the curing rate and this study indicates that laser heating is the better heat source in efficiency terms. Defects such as fibre misalignments, voids, and delamination are induced during manufactuirng are explored. The sources of these defects have been discussed herein as well as the secondary defects caused by them with the consideration of residual stress impact. The presence of manufacturing defects has been identified to influence the strength and stiffness, interlaminar shear strength, toughness, and creep performance. In addition the study shows there is a need to explore the state of the art in defect characterization during manufacturing for TCP. The in-situ characterization aims to derive high-quality TCP with reduced defects and need for repairs, and increased production rate in safe and eco-friendly conditions while maintaining the current manufacturing process.

Keywords Thermoplastic composite · Manufacturing defects · Manufacturing techniques · Processing parameters · Thermo-mechanical performance

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1 Introduction

This section provides the concept behind the manufacturing of thermoplastic composite pipes (TCP), the beneficial features, and an overview of defect induction into the pipe. It also provides the objective of this work and an attempt to address the knowledge gap.

1.1 Background Study

Pipes are vital in the energy industry for the transportation of fluids. The thermoplastic composite pipes (TCP) are fully bonded pipes designed for high-level performance applications, weigh about one-tenth that of metal-based pipes counterparts and have a key advantage over other forms of flexible pipes in that it has lower manufacturing cost. This is related to reduced capital investment cost, easier pipe construction, and an uncomplicated end-fitting

Fig. 1 Predictions on the global fibre reinforced polymer composite market **a** global fibre reinforced polymer pipe market by fibre type [5] **b** the market growth of composite pipes for oil and gas applications according to regions [6]

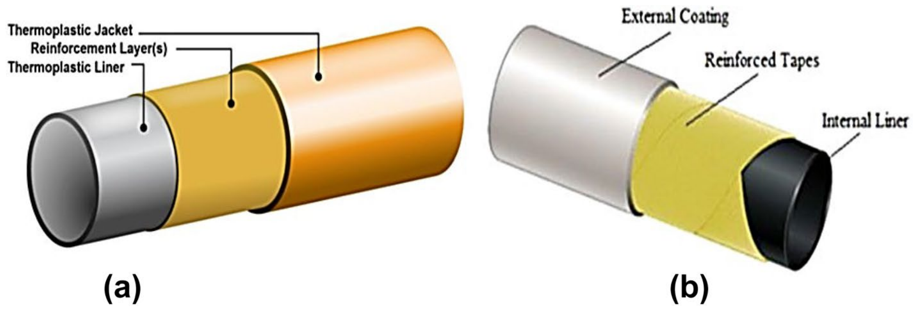


Fig. 2 Schematic illustration of **a** TCP [9] and **b** reinforced thermoplastic pipe (RTP) [10]. Although RTP and TCP consist of quite a similar composition, RTP can also be reinforced with steel wire and are mostly unbonded

design [1–3]. A combination of all these advantageous features makes pipes spoolable on reels, smaller drums, or subsea pallets. Hence, smaller vessels can be used for conveying and installing long spans of TCP which makes TCP appealing economically and logistically even in remote offshore (or onshore) fields where using the traditional heavy-lift vessels is difficult and expensive. Another appealing factor is that through the melt-fusing procedure for TCP, the pipe length can be changed and allows end fittings installation onsite [3]. TCP offers several advantages over other forms of flexible pipes. This is due to possessing high fracture toughness, great fatigue resistance, infinite shelf life, low storage cost, excellent solvent and corrosion resistance, and great damage tolerance [4].

It is worth a note that the global fibre reinforced polymer market for high-performance structures is steadily growing, and it is expected to reach US$ 28.7 billion by 2027 at a CAGR of 8.3% with glass fibre reinforced polymer composite being the most dominant of other forms of fibre reinforced composites which can be attributed to their relative cost-efficiency according to performance (depicted in Fig. 1a and b) [5]. Specifically, the composite pipe market for oil and gas applications was valued at USD 2.8 billion in 2016 and projected to reach USD 3.6 billion by 2025, at a CAGR of 5.2% with a steady increase in usage growth across the different regions expected [6]. Fibres or tows presently account for most of the reinforcement in use, it can be established that the use of it will keep growing.

The basic flexible composite pipes consist of three layers. They are the liner, the fibre reinforcement layer, and the outer layer that is called weight coating or jacket (see Fig. 2). The outer layer protects the pipe from external influences and the liner contains the liquid transported through the pipe. The reinforcing layer can be attached to the liner, thus bonded, loose fit, or unbonded. In the reinforcing layer in the unbonded pipe, the fibres are woven, whereas for bonded, fibres are embedded in a matrix and disposed of unidirectionally. It is important to consider the operating conditions of the pipe before deciding on the appropriate reinforcement layer and thermoplastic depending on the acidity of the transported fluid and the pressures and temperatures involved during operations [7, 8].

For the benefit of the reader, it is important to mention the difference between the TCP and reinforced thermoplastic pipe (RTP) which are all under the flexible composite pipes (FCP) category. For a start, the FCP is a continuously spoolable pipeline product made up of a reinforced thermoplastic liner protected by a shielding/reinforced layer and can be used in water and hydrocarbon transportation. FCP is a proven technology for offshore operations while significant progress has recently made pipes acceptable to an offshore environment in shallow water depth. A wide range of FCP products dependent on the varying materials used in the fabrication techniques results in varying performances has been applied in the oil and gas industry. Reinforcement materials (i.e., fibres and stripes) differ significantly leading to a huge variation in performance. Reinforcement can either be fully bonded to an integrated matrix or unbonded in tapes or string which is fastened by adhesives, resulting in different prices and applications [11, 12]. It can be further split into unbonded FCP and bonded FCP which includes reinforced thermoplastic pipe (RTP, semi bonded) and thermoplastic composite pipe (TCP, bonded).

RTP generally refers to the reliable great strength synthetic fibre (aramid, carbon, or glass) or great strength steel wire strips reinforced thermoplastic piping systems, although other forms of combination can be used. The thermoplastic matrix used in fabricating RTP is mainly Polyethene (PE), Polyamide 11 (PA11), or Polyvinylidene fluoride (PVDF). Typically, RTP which can be used both onshore and offshore has unbonded layers because hot melt adhesives are used to fasten the coated and liner layers to the reinforced layer. RTP is available in pressure ratings from 0.435 to 6.527 Ksi and the recent novelties for RTPs are RTP for high service temperature conditions and gastight RTP.

The reinforced thermoplastic pipe (RTP) is a composite flexible pipe originally developed for onshore oil and gas production, but it is now increasingly being used in selected offshore projects for the merit of corrosion resistance, lightweight, and low cost for installation [13]. It is already being used for offshore applications in water depths ranging from about 30 m to 900 m [10] while TCP is a spoolable, fully bonded, thermoplastic composite pipe with glass or carbon fibre reinforcements as indicated in Fig. 2. Examples of TCP and RTP pipes details and applications are detailed in Table 1. Although TCP has a similar material setup to RTP, TCP is designed for higher pressure and temperature range applications (Table 1) based on the following reasons (i) TCP utilizes great performing thermoplastic resins and high strength fibre reinforcement, and (ii) TCP layers are totally bonded to one another via the melt fusion manufacturing process, this yields a better general performance characteristic than RTP of similar material.

Although numerous studies have been done on thermoplastic composite structural defects and the damage mode of metal-based pipes, there is a lack of research on the induced defects in TCP that are formed during the manufacturing process, and this justifies the need to understand the material to manufacture relationship and the effect of the identified defects on the operational performance of TCP. Noteworthy, with these being a holistic review, the reinforced layer which is a laminated material is the most critical layer of TCP as it largely determines the material behaviour, and this results in more emphasis on them. For this reason, the purpose of this review covers the appreciation of TCP and the material composition which is a fibre-reinforced thermoplastic structure. Previous research on fibre and thermoplastic matrix properties is presented here. The functionalities of the fibre and matrix with the fibre-matrix relationship and interaction are also discussed. The key research question is the discernment of the applicable defects and their classification as well as the identification and analysis of factors behind the development of defects. Identifying these factors will assist in understanding these defects and in establishing systems for predicting defects. This will be achieved by an examination of the current manufacturing techniques used for TCP and the comparison between these techniques is thoroughly highlighted with an overview of vital components such as the heat source and consolidation. The manufacturing-induced defects and the factor behind their formation are subsequently

Table 1 The range of currently produced composite pipes and comparison [3, 14–16]

Material	Applications	Operating conditions	Service	Features
TCP				
Carbon fibre/PVDF	Riser (under development)	~121 °C and 15 ksi	Hydrocarbons	Can handle the pressure of up to 689 bar $(TCP = 10\times RTP)_{pressure}$ It can be used in 3,000 mwd and has been proven with 2,140 mwd. Does not require additional measures for gas services and can efficiently handle all services which include sweet and sour crude, gas and the whole well stream. Can go up to 7.75 in true bore liner diameter manufactured in a continuous length of at least 3,000 m. Also, the maximum applied length per spool relies on permitted drum size, notwithstanding a standard road conveyed drums can be provided in lengths of at least 600 m.
Carbon fibre/PA12	Flowline-Jumper spool	~80 °C and 10 ksi	Hydrocarbons, seawater	
Glass fibre/HDPE	Intervention jumper- jumper spool-Flowline	~65 °C and 5 ksi	Water, methanol, Hydrocarbons, acids	
Carbon fibre/PEEK	Intervention systems, flowlines, and jumpers	≤ 20 Ksi	Hydrocarbon, water, and gas service	
RTP				
PE100+ , (Bimodal HDPE)	High-pressure water injection pipelines, water transport and distribution, effluent water disposal, oil and gas flow- and gathering lines, (domestic) gas pipelines, and well intervention	~65 °C and 0.45 – 1.5 ksi	Hydrocarbon, water, and gas service	Handles pressure of about 70 bar Used onshore and in offshore shallow water of about 30 m. Cannot handle gas service in high pressure (42 bar maximum operating pressure) and requires additional procedures to be carried out e.g. gas venting. Limited true liner bore diameter of 5.6 in inner diameter can be supplied at a length of 300 m per pool

emphasized. Additionally, the effect of these defects on the composite microstructure property and performance is also predicted.

2 Manufacturing Factors

Here the focus is on the uniqueness of TCP and the material composition which is a fibre-reinforced thermoplastic structure. A summary of previous research on fibre and thermoplastic matrix properties is also presented here. The functionalities of the fibre and matrix with the characteristics are also discussed. It also provides the current manufacturing techniques used for thermoplastic composite pipes. The comparison between them is also highlighted with the vital components such as the heat source and layup procedures.

2.1 TCP Material Composition

2.1.1 Type of Fibres

Several concepts have been suggested for the appropriate use of materials and among them is the one material concept. TCP comprises thermoplastic components which are weight coat (thermoplastic and metaltite), reinforced layer (thermoplastic and carbon/glass fibre), and liner (see Fig. 2). Therefore, the pipe is made of one solid wall. One material concept means that all the layers are of the same thermoplastic matrix reinforced with either carbon or glass (E and S) fibres (aramid fibres are not used due to poor pressure resistance) applied on the tapes, by impregnation to a thermoplastic polymer matrix. The role of a filler or fibre is to enhance the load ability of the polymer, while that of the polymer matrix is to protect the fibre and proffer efficient load distribution on the entire body [17–22]. The fibre used for TCP determines the pressure rating, although carbon fibre has a high cost per unit weight, they have better performance among fibres while glass fibre (E-glass) can be used as an alternative when cost efficiency is considered [23–27]. The same polymer matrix of the liner is used for impregnation. Therefore, the tape is wound to the liner, and it is melting fused onto the liner and the next tape is placed on the tape beneath. Through this method, a stiffer and stronger pipe is produced from one polymer and one fibre system [28]. Figure 3a below depicts a schematic representation of the composites.

Directional fibre placement leads to anisotropic (differences in the magnitude of the physical property when measured from different directions) mechanical properties regardless of the order, while the strain and stress resistance increase with the fibre dimension. The materials must interact at the interface to facilitate stress distribution and they should be chemically compatible. The high specific stiffness and strength of this property [30, 31] have a significant influence whereas other material properties which include the coefficient of linear thermal expansion (CTE), electrical and thermal conductivities are also anisotropic. Most times, increasing material properties are noticed across the fibre direction whereas the composite properties are reduced in the reverse direction [17, 32, 33]. The typical mechanical properties of several reinforcement fibre types can be found in Table 2.

Any microcracks within the interface between the polymer matrix and the fibre can lead to a major loss of strength and stiffness [34] and consequently, self-healing functionality was suggested by Norris et al. [35], Hamilton et al. [36], and Hofstätter et al. [34] for the termination of defects automatically. The wide use of advanced fibre-reinforced materials

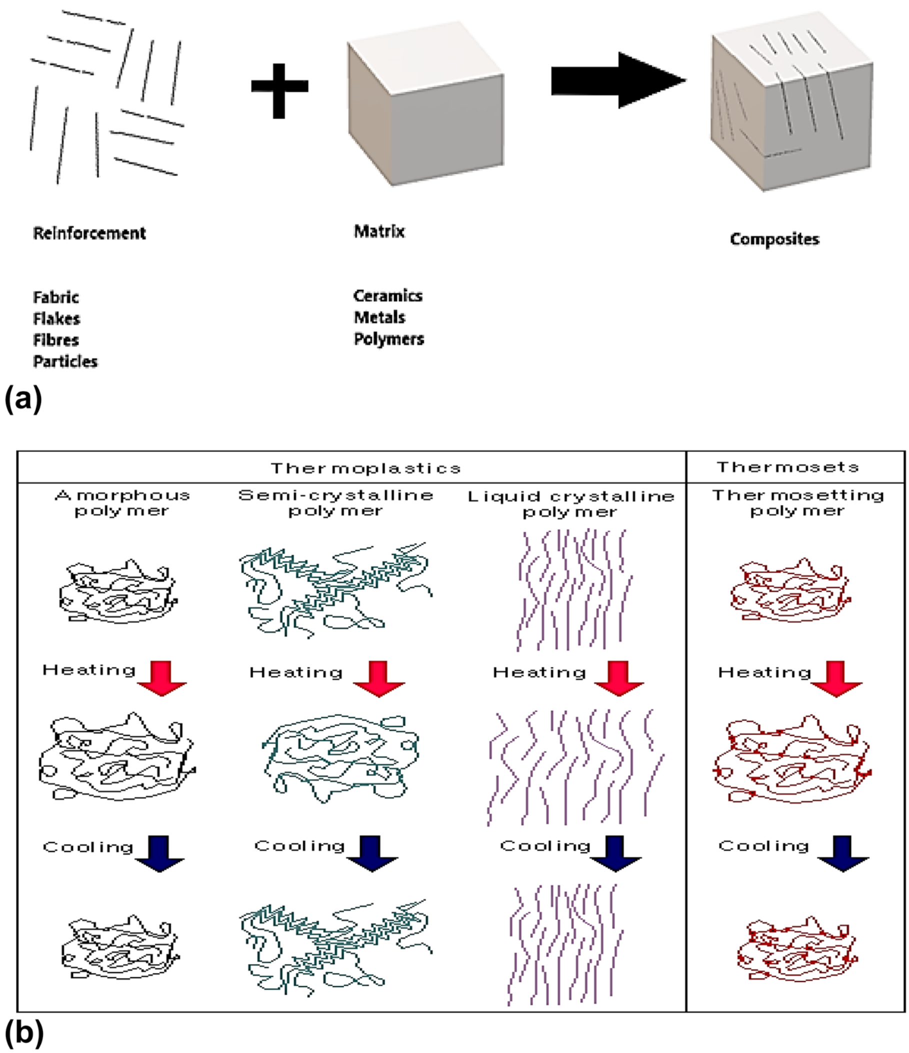


Fig. 3 Schematic illustration of **a** reinforced composites **b** microstructural behaviour of polymer matrix types (no fibre) with the effect of heating and cooling [29]

is limited by the high cost of manufacturing. However, with the rapidly evolving manufacturing technique, it is becoming possible to produce composite pipes at a cheaper cost whereby broader applications. Fibre reinforcement exhibits a physical change rather than a chemical change in the material to fit an engineering application [37, 38]. Generally, the desired functional requirements of the fibre in a fibre-reinforced polymer composite pipe are that the fibre should have a high modulus of elasticity for the efficient utilization of reinforcement; high ultimate strength; the variation in strength between individual fibres should be low; stable and capable of retaining fibre strength during handling and fabrication and the diameter as well as the surface of the fibre should be uniform.

Table 2 Typical properties of composite reinforcement fibres for composite pipes

Fibre type		Features		Properties				
		Advantages	**Limitations**	**σ_b (GN/m^2)**	**E (GN/m^2)**	**ρ (Mg/m^3)**	**CTE (°C^{-1})**	**Thermal conductivity (W/m^{-k})**
Carbon		Extensively Rigid High compressive/ tensile strength Low CTE High strength to weight ratio High electromagnetic shielding	Corrosive to metals in contact with carbon fibre reinforced polymers Low impact strength High cost Very brittle	1.9 – 2.41	55–110	1.9 – 2.16	-0.13E-6 – -0.2E-6 (L) 10E-6 – 15E-6 (T)	120–300
	E-glass (electrical insulators)	High energy absorption Cost-efficient	Less rigid than aramid and carbon fibre	2.4 -3.45	72.4	2.54 – 2.58	5.0E-6 – 5.4E-6 (L) 5.0E-6 (T)	1.03
Glass	S-glass (tensile strength > E-glass)	Can be modified in varying patterns Huge knowledge base and broadly used High tensile strength Moisture and chemical resistant Compatible with several resin types Electrical insulators	Low strength to weight ratio Lower strength in comparison to carbon fibre	4.5–4.89	85.5 – 86.9	2.46 – 2.49	1.6E-6 – 5.6E-6 (L) 5.6E-6 (T)	3.03

Table 2 (continued)

Fibre type	Features		Properties				
	Advantages	**Limitations**	σ_b (GN/m^2)	E (GN/m^2)	ρ (Mg/m^3)	CTE (°C^{-1})	Thermal conductivity (W/m^{-k})
Aramid	Good in-service performance High strength to weight ratio High impact resistance Chemically resistant High toughness Lightweight High energy and absorption and vibration High crack resistance	Great challenge in cutting, preparing, or processing High cost Low compressive strength Poor ultraviolet resistance Absorbs moisture (~ 3.5%)	3.6 – 4.1	83–186	1.44 – 1.47	-2E-6 (L) 60E-6 (T)	0.04 – 0.075

L longitudinal, *T* transverse, σ_b Tensile strength, *E* Young's modulus, ρ mass density

2.1.2 Polymer Matrix Selection

The polymer matrix is required to bind the fibres together and protect their surfaces from damage during handling, fabrication, and the service life of the composite. It also determines the temperature requirement and rate of heat flow capacity of TCP. The level of chain branching is a necessary factor for the determination of the mechanical properties of the polymers which include tensile strength, stiffness, impact fracture toughness, and draw ratio. It is also influential in crystallinity and density [39, 40]. Following the occurrence of nucleation, the produced crystallite has continuous growth, and this integrates the material with melting. As growth continues, the crystallizing mass reaches a certain growth structure which is a continuous process, until it is outside the nucleation point. The crystallinity makes the material strong, but it can also make it brittle. A completely crystalline polymer would be too brittle to be used as thermoplastic. The amorphous regions give a polymer toughness ability to bend without breaking and the ability to absorb impact energy. These are both good properties to have in a TCP as it influences the minimum bend radius. One of the methods for determining polymer crystallinity is the differential scanning calorimetry (DSC) (from thermal analysis) and density (via weight fraction) are the fastest and most reliable techniques for determining the degree of crystallinity [39]. The weight fraction approach used for evaluating the degree of crystallinity is, $X_c = \frac{\rho_c}{\rho}(\frac{\rho-\rho_a}{\rho_c-\rho_a})$, where ρ, ρ_a and ρ_c is the densities of the sample of interest, total amorphous sample, and total crystalline samples respectively. The technique for thermal analysis relies on the heat fusion measure (ΔH) of the polymer of interest which is done using differential scanning calorimetry (DSC), the value obtained is compared to the total crystalline heat of fusion (ΔH_f), the degree of crystallinity (X_c), $X_c = \frac{\Delta H}{\Delta H_f}$.

During TCP manufacturing, the molecular weight is the major structural unit of polymer flow characteristics at higher temperatures which is beyond the melting point (semi-crystalline polymer) or glass transition temperature (amorphous polymer). The molecular weight (Mw) details the polymer chain length which can be linked to the mechanical properties. In the polymerization process, all the chains do not grow to the same length which results in the distribution of chain lengths/molecular weight inside the polymer [39]. Due to phase changes, thermoplastic structures can be categorized into amorphous polymers and (semi) crystalline polymers (Fig. 3b). With low molecular weight polymers, the chain entanglement is not a factor since the molecular weight of the polymer is directly proportional to the zero-shear viscosity. The rheological measurements are ideal for the evaluation of the effects of differences in the molecular weight of the resins, and slight molecular weight differences that are evident in large changes in viscosity [41]. A high molecular weight distribution such as a thermoplastic and fibre composite can increase the mechanical induced cross-linking reaction between the polymer and the fibre, which reduces their window of processability [42].

Furthermore, thermoplastics can undergo hardening or soften repeatedly through a decrease or increase in temperature, respectively. Although thermoplastics are recyclable, chemical changes such as oxidation and thermal degradation may occur during processing and hence a recycled polymeric property will differ from that of a virgin polymer [43]. TCP thermoplastics are all semi-crystalline, and the earliest and most basic model of semi-crystalline polymers is a fringed-micelle model [39, 44]. This model has a long polymer chain length that makes it function between crystalline and amorphous as the chain will not maintain its order throughout the length resulting in the amount of crystalline material being less than 50% [45].

Finally, thermoplastics may exhibit a partial cross-linking which indicates that they possess reversible rheological, mechanical, and thermal properties whereas thermoset polymers are totally cross-linked [46]. This influences the toughness and reinforcement strategies of the TCP. It follows that the polymers are regarded as inert when it does not for example dissolve, react or swell when in contact with other substances or if the rate of the reaction is very slow. Some thermoplastics can be described as inert that is, when the inert polymers are reinforced with fibres, the composites produced are inert and possess superior mechanical performance, thermosets such as epoxy while thermoplastics such as polyamides are not regarded as inert because they are moisture sensitive (hydrophilic) [47, 48].

2.2 Manufacturing Techniques

Composite materials which include TCP can be modified through manufacturing, and this is a crucial step in obtaining the desired TCP structure which begins with the design for manufacturing (DFM), and the selection of the suitable technique to be used in achieving them [49]. Each structure has a form of defect where the presence of these defects can sometimes be beneficial and purposely induced into a structure to meet specific requirements; a lowered threshold of measured defects is applied in defining a defect-free structure. The manufacturing and processing techniques produce defects that are induced into the structure right from the early stage of the TCP life cycle [50, 51]. For the manufacturing cost for composite structures to be efficient, the effect of the manufacturing parameters on defect formation must be evaluated. This involves a level of performance-based knowledge on the defects (for both manufacturing and in-service) and the quantification of the defect which affects the performance of the structure. Furthermore, for consideration of controlled manufacturing cost reduction, it is essential that the influential manufacturing parameters be quantified and then modified to minimize cost.

TCP uses a one-material design concept in which the internal liner, the composite layers, and the outer coating are all from the same polymer material. The inner liner is the fluid barrier under the reinforced layer. The vital parameter of the liners is the chemical resistance and permeability level. Through the extrusion process, a smooth bore surface is formed which encourages a swift and high flow rate. The liner possesses a high yield strain which aids the liner in following TCP motion and remains within the elastic range of the material. The vital structural layer of the TCP is the laminate reinforced layer that provides the load-bearing capacity. It is made up of several unidirectional (UD) tape layers with a predetermined orientation angle based on application. The reinforced layer is then covered with a coating to provide protection against fluid permeation, environmental elements, damage, and warping. Sometimes a weight coating may be extruded to enhance the bottom stability. As mentioned earlier, the TCP pipe is made with an in-situ consolidation manufacturing process that melt-fuses all layers together, to form a strong and stiff solid wall construction. Furthermore, the properties of the thermoplastic matrix enhance the allowable strains which provide TCP with spoolable and flexible characteristics. A total combination of all these factors makes TCP collapse-resistant, spoolable, lightweight, and corrosion-resistant [1–3, 28].

As noted by Echtermeyer et al. [52], the current recommended practice for the offshore application of fully bonded TCP (pipes and materials) is through the DNV GL-RP-F119. The approval of this standard offers clients a reduction of implementation cost by the manufacturers and end-users while similarly establishing functionality and safety throughout the design life. However, requires a high temperature and pressure manufacturing process (see Fig. 4) which can, unfortunately, hinder the full use of TCP due to the higher cost

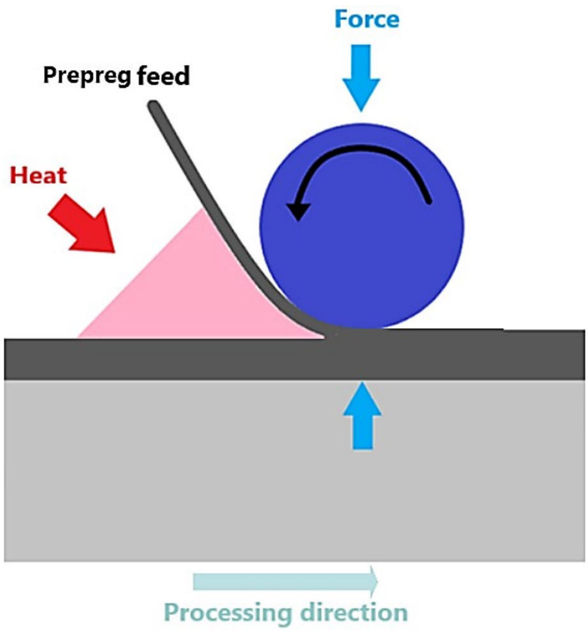


Fig. 4 Graphical representation of thermal fusion process and processing challenges

of manufacturing currently countered with melt fusion bonding of TCP. This technique is anticipated to replace conventional assembly and joining methods such as adhesive bonding, co-consolidation bonding, mechanical fastening, and solvent bonding.

The use of traditional joining methods to join thermoplastic composites is costly, difficult, and labour-intensive [4]. The manufacturing parameters are challenging to handle properly during the manufacturing stage, they do tend to induce defects during manufacturing and in the long-term result in service failure modes. These include yielding, fracture, debonding from layers, puncturing scratches, permeability change, wear and tear, cracking, rapid gas decompression, swelling, thermal softening/hardening, photodegradation failures, poor chemical resistance, marine growth, and morphology change [52]. Furthermore, the high pressure and temperature conditions used in the melt fusion bonding of TCP must be optimized during consolidation as a low temperature and pressure situation can induce poor adhesion (bonding) between layers while a heightened pressure and temperature can generate material degradation. TCP manufacturing is a continuous process, a pictorial representation is presented in Fig. 5.

The elements that make up the production line are also highlighted. First, the liner is extruded and linked between the payoff carousels and take up (1 and 6). Pipe manufacturing occurs between the carousels in the winding station (4), where melt fusion occurs through composite tape winding as described in the techniques above. During the process, both pressure and heat are incorporated to attain an efficient bonding and consolidation between the layers (this is the most vital aspect). The caterpillar (5) controls the speed of manufacturing and drags the pipe through the winding station, then the pipe is rolled into a take-up carousel. (6) After a single run, the pipe recoils in the payoff carousel, and the whole process is repeated for the next layer. After laying to the designed thickness, the pipe is then coated. This coating is a thermoplastic polymer based where metaltite is applied through various equipment and then the pipe is heated, extruded, and cooled in a single procedure. In this regard, the process can take a duration that ranges from weeks to months

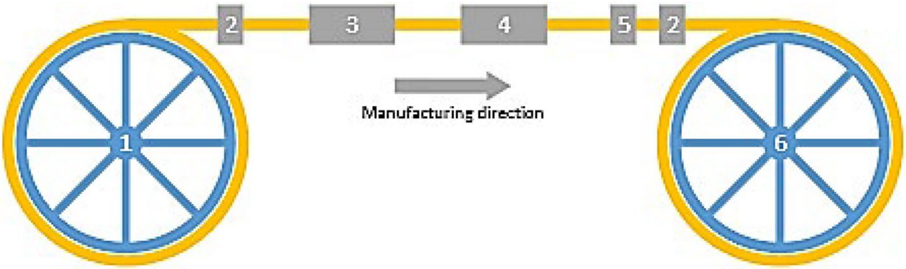


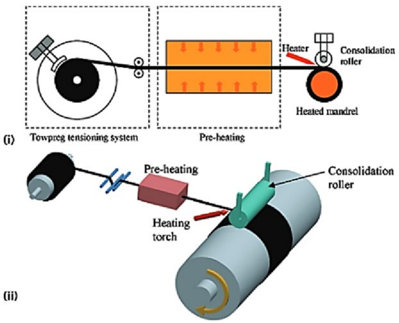
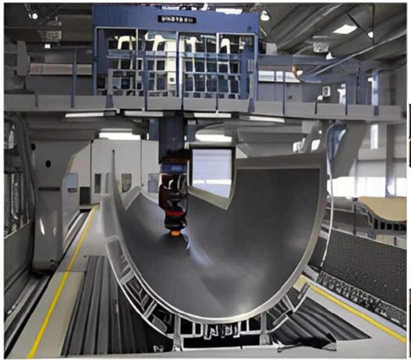
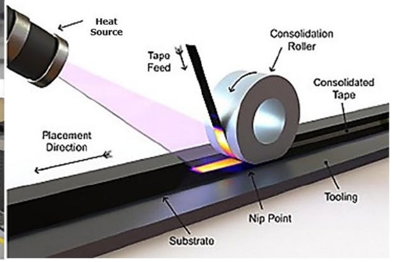
Fig. 5 TCP manufacturing layout 1: pay off the carousel, 2: trans versing unit, 3: length measurement system, 4: winding station, 5: caterpillar, 6: take up carousel [53]

to acquire the requirements on the thickness and length [53]. However, with thermoplastic composites being manufactured at a high processing temperature and consolidation pressure, this is accompanied by viscosities in the range of 500–5000 Pa.s which limits the full use of thermoplastic composites. With the melt viscosity being on the high side, it will be a challenge for the molten polymer to impregnate the fibres and influences the total wetting of the bonding layers in a melt fusion manufacturing process which can subsequently among other factors induce defects [54, 55].

Firstly, it is worth noting that this work focuses on the defect formation induced through varying manufacturing with special attention to high-performance composite manufacturing and is therefore biased towards automated manufacturing techniques. Automated continuous techniques have increasingly attracted the interest of the industry due to the faster rate of deposition, lower cost, and repeatability of the process over hand lay-up techniques [56]. Filament winding (FW), automated tape laying (ATL), and automated fibre placement (AFP) are the present automated fabrication techniques (labelled a, b, and c in Table 3), and they can all be modified depending on the scale and application of the final product. The basic differences between the most efficient techniques that have been used in composite manufacturing are summarised in Table 3. These techniques are proving to be cost-efficient as they are totally automated and have a single consolidation step process with the flexibility to modify the winding speed and tape tension. Thermoplastic and thermoset unidirectional (UD) prepreg are often used for the automated production of modern high-performance composite materials. The "pre-pegs" (pre-impregnated fibres tapes) are ready-made tapes made from fibres within a polymer matrix. They are used for producing great quality, high-performing composites. They can be laid either by manual or mechanical means in layer format at varying orientations to produce a structure. The different processability of the matrix systems and the different molecular structures of thermosetting and thermoplastic semi-finished products are the main differences in their automated manufacturing process [57]. The main drawback of prepreg is higher manufacturing costs [56, 58].

To promote fibre impregnation in the manufactured prepregs, methods such as commingled fibre, film stacking, and powder impregnation are mainly used. The pull tension from the continuous fibre and heat source temperature is closely related to impregnation and consolidation [26]. In general, the automated set-up consists of an optional pre-heater to make the material reach the suitable temperature, prior to passing the winding chamber, it is held at an operating temperature higher than the melting point of either thermoplastic or thermoset polymer matrix. The spot where the tape and the surface of the substrate meet can be heated greater than the melt temperature by heat sources (e.g., hot gas torch, infrared and laser system) in a continuous

Table 3 The distinct features of the different manufacturing techniques

Filament winding (FW)	Fibre placement (AFP)	Tape laying (ATL)
		
(a) Illustration of thermoplastic filament winding, (i) schematic; (ii) winding process [59]	(b) An AFP machine laying into a female mould (c) Representation of the automated fibre placement head [57]	
This is an automated open moulding process where a rotating mandrel is used as a mould	Fibre placement systems are an automated process of heating and compacting a resin pre-impregnated fibre in a usually complex mandrel	Tape laying involves wide unidirectional tapes being laid on the part mould using a loaded roller system
It entails the winding of filaments under tension on a rotating mandrel	AFP is similar to ATL but utilizes narrower prepreg tapes. As narrower tapes are better for sharply curved surfaces	ATL is used to lay wide prepreg tape onto a surface
Suitable for manufacturing pressure vessels	AFP could be used to manufacture more complex geometries	It is suited for the manufacturing of bigger parts of simpler geometry
Geodesic and non-geodesic path	Geodesic and non-geodesic path	Geodesic and non-geodesic path
Convex or concave surfaces	Flat surfaces	Flat surfaces
The winding angle of 0–90°	Ply angle of 0–90°.	Ply angle of 0–90°
Endless fibre	Ease of termination and resumption	Ease of termination and resumption
In-situ consolidation	In-situ consolidation	In-situ consolidation
Heat applied directly to nip point	Heat applied at broad delivery	Heat applied at broad delivery

in-situ consolidation process whereby the layup head is in motion. The consolidation roller functions as a compactor and the consolidation speed are restricted by the time needed for autohesion (direct-bonding or self-bonding through a molecular bond, inter-diffusion, entanglement) and intimate contact [60]. Basically, the roller pressure, heat intensity, and speed of consolidation perfectly describe the window of processability for online consolidation.

In terms of analysis, online consolidation can be further split into localized melting, non-isothermal consolidation, and controlled curing. It is preferable that the resin melts within the region of the nip point where the incoming prepreg and consolidated substrate merge. The consolidation is non-isothermal and requires steady heating, compaction, and cutting, which leads to a significant temperature difference within the deformed zone [61]. If two surfaces are joined without contact from applied pressure, openings appear at the interface and autohesion fails to occur without intimate contact intervention. Thus, introducing a pressure field to compact the viscous matrix, fill the openings, and derive sufficient contact is vital for a favourable fusion bonding. It is noteworthy that polymer chains take a relatively shorter time to diffuse for semi-crystalline thermoplastics when compared to thermosets. Hence, autohesion finalizes immediately after the two molten surfaces meet, and the microstructure of the contact region is similar to that of any other part of the structural section [61–65]. The final phase of the online consolidation is the curing of the consolidated part.

Although the properties of the bulk thermoplastic composite material are influenced by the whole processing cycle, the cooling rate is vital for the degree of crystallinity and the morphology of the matrix. Usually, the slower cooling rates yield a greater degree of crystallinity which correlates to a rise in compressive and tensile strength and solvent-resistance of the polymer while the tape laying is mainly used for large surfaces with tolerable curvature which includes pressurized vessels e.g., pipes. However, concave, and complex winding paths can be done with this technique [56]. Generally, these techniques all apply to the thermoplastic in-situ consolidation concept where thermal energy is first input to heat the incoming tapes and the already deposited layer (substrate) to the matrix melt temperature. A compaction force through the consolidation rollers produces pressure that fuses the molten heat-affected region and the layers immediately after placement to facilitate adhesion and prevent the formation of air pockets that can produce voids. An in-situ quality monitoring system can be introduced to detect deviations in certain parameters that affect the quality of the final product.

The manufacturing innovation with thermoplastics eliminates the need for autoclaves for curing typically required in thermosets however it does come with a challenge of high viscosity control during manufacturing. Further, when thermoplastic composites are adequately consolidated temperature curing conditions can negatively affect their mesostructured and their macro-performance when subjected to either re-heating or cooling (thermal de-consolidation) [66]. Certain properties which influence the final product on the surface are surface waviness and surface roughness. The surface roughness of the individual layers should be high to facilitate an improved bonding between the layers, especially for round surfaces such as a pipe. Therefore, preconditioning of the feed materials prior to manufacturing is recommended and this can be achieved mainly by heating the feed materials which improves the surface roughness. Similarly, the post-conditioning of the final part is expected to improve the surface finish quality.

2.3 Temperature Conditions

2.3.1 Heat Source and its Application

Consolidation and bonding are mainly achieved at the interface region by the concurrent application of localized heat (layer softening) and pressure (bonding). Therefore, thermal behaviour plays a vital role here as it provides details on optimizing the temperature distribution during processing. The heating system in the compaction device is among the most challenging elements in literature [67–69]. Basically, the melt fusion bonding process comprises two composite parts/plies which are bonded through melting their surfaces while subjected to pressure [41]. There are various heating procedures that enable the attainment of this level of bonding which includes discontinuous and static procedures where the plies are initially stacked and further consolidated through continuous methods (e.g., laser, hot gas, or infrared (IR) heating) whereby consolidation occurs while the tape/prepregs are kept in motion [70, 71]. In automated fabrication techniques, the heat source is a vital factor in the manufacturing efficiency, final product, and manufacturing costs. Several sources of heat can be utilized in preconditioning and subsequently melting/softening the interface region. These include flame spraying, induction heating, resistance welding, oven, laser, hot gas torch, and infrared heaters have been assessed in the literature [68]. The results indicate that the diode laser type has the most favourable review and suggestion that the hot gas torch, flame (infrared), and laser systems as the heat source forms the highest rankings for thermoplastic matrix [72]. Table 4 outlines a basic comparison of the various heating sources applicable to thermoplastic composite winding.

In all three concepts, the incoming tapes may be preheated, or heat may be applied only at the nip-point to reduce the void and thermal energy needed in the nip area so that the tape is less likely subjected to overheating. Depending on the technique used, a combination of these heating elements can contribute to a near-perfect consolidation. The pressure is applied to the material using a series of rollers. The process is highly non-isothermal, subjecting the material to multiple heating and cooling rates approaching a high-temperature rate. Firstly, the studied systems were mostly on the hot gas torch which subsequently evolved to the lasers which started as the carbon dioxide (CO_2) laser heat source type, then to Nd: YAGs type and nowadays the laser diode type which is considered the best option. The variations in the heating solutions have been applied and given varying results as expected; the hot gas torch exhibits low energy efficiency and delays in responding despite its flexibility and cheaper costs, while the infrared heat source still struggles to meet the demands for heating at the nip point.

Laser has now become the best alternative due to their fast response and good energy efficiency. Additionally, for the selection of lasers to use, it is important to know their interaction with the materials, particularly for the ability of radiation absorption by the material.

Table 4 Benefits and disadvantages of heat sources [73]

	Hot Gas Torch	Infrared Light	Laser beam
Response Time	—	+–	+
Weight	++	+	–
Energy Efficiency	—	+–	+
Size	++	+–	–
Price	+	+	–

With + and – signifying yes and no respectively

For the CO_2 laser types (wavelength (λ) = 10,600 nm) where the matrix has high absorbance while for the diode (λ = 805–940-980 nm) and Nd: YAG lasers (λ = 1064 nm), the matrix is transparent to radiation, transmitting and reflects the whole energy. Hot gas torch remains the most used heat source for automated fabrications and has been broadly analysed based on their low capital cost [68]. However, the cost increases when nitrogen is used as the gas to avoid surface oxidation at higher temperatures [67]. Hot gas heating is highly effective for attaining high temperatures. However, this system is renowned for wasting a significant amount of energy due to its convective heat transfer medium which is regarded as a lengthy dynamic response time, and this reduces its heating efficiency and reduces the process control performance which indirectly makes attaining the necessary general production become a challenge [67, 69]. For the hot gas torch systems, air can be used as the gas [74, 75], however, nitrogen is widely employed for setups with a single torch [76–78] or two torches [79–83].

The initial purpose of the infra-red (IR) lamp is to augment the nitrogen hot gas torches and subsequently replaced the torch system which had challenges with controlling heat transfer in the nip region because of the stagnating hot gas flow. IR lamps are relatively cheaper and extremely easy to control to ensure the possibility of carefully controlling the melt region temperature. IR lamps are a highly efficient heat source, especially for carbon-based materials, considering that the energy is almost fully absorbed [84]. However, the limitation of the IR lamp system is the poor ability to provide high specific energy which leads to heating material regions that are not supposed to be heated [41]. Furthermore, IR lamps are relatively slow to heat and cool plus have the likelihood of holding substantial residual heat when turned off [85]. They can be applied as pre-heaters [66, 72–74] and as the principal heat source [62, 86]. The laser heat source provides several advantages such as the ability of a direct appliance of elevated heat intensity to a specific area or at a localized position [87, 88] which reduces the induced stresses and the likelihood of material degradation [88–90]. Lasers are effective and enable robust heating based on the absence of convective hot gas retardation and the rapid response time [91–93], where for example, the fibre laser (depicted in Fig. 6a) showed that it is 50% more efficient than the hot gas torch heating system when subjected to similar setup conditions with regards to their productivity [94].

The major limitations are the cost in terms of the purchase [95] and their large size limits the geometric ranges for part production, and this may need solid health and safety measures [56]. For the CO_2 form of laser systems (10,600 nm wavelength), the resins are extremely absorptive while for modern lasers, which include diode (810-980 nm wavelength), Nd: YAG, and fibre (1064 nm wavelength) laser systems, the resins are more transparent. This implies that using the CO_2 laser induces the risk of thermal degradation and oxidation at the resin surface of the prepregs prior to influencing the matrix-fibre interfacial adhesion. CO_2 lasers can be too big for a focused mounting on the placement head during automated fabrications [96]. Additionally, due to their lengthy wavelength, the suitability for fibre optic delivery is hampered as they have higher adsorption rates of the wavelengths [69, 96]. Typically, the CO_2 laser output is a tiny round point while a rectangular or linear distribution is the desired choice because uniform heating across the width of the substrate and incoming tape is produced [96]. However, this can be corrected by converting the round point into a linear source by using a galvanometer scanner [97] or by applying zinc selenide (ZnSe) lenses [70, 88, 94]. Contrastingly, the diode, fibre, and Nd: YAG laser wavelength enables varying heating procedures, here the laser light is completely absorbed by carbon fibre as carbon fibres are extremely thermally conductive across the length, and this ensures that

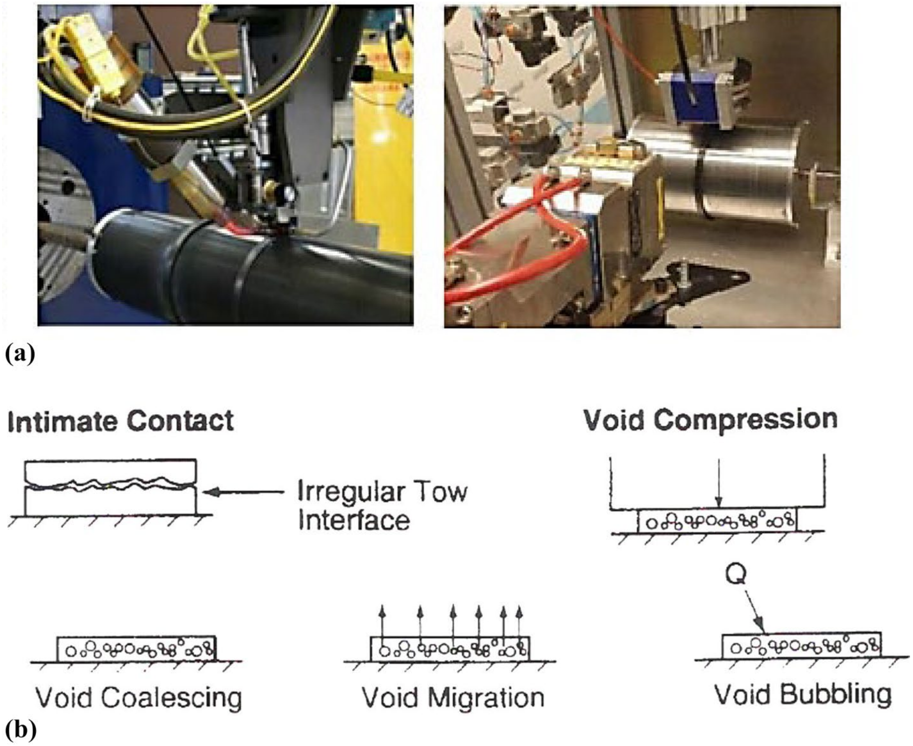


Fig. 6 **a** AFP set-up with (left) hot gas torch heating and (right) laser heating systems [68] **b** Mechanism of void elimination in thermoplastic placement process [73]

adequately controllable and uniform heating of the prepregs can be obtained. Hence the challenge of thermal degradation or charring of the polymer matrix is eliminated [69, 98, 99]. Basically, diode lasers are superior to Nd: YAG lasers because of the scalable principles applied to boost an efficient and optimal design approach [100]. As previously noted by Yassin and Hojjati [68], a more experimental study addressing the heating procedures of the modern manufacturing process is lacking in the literature.

It is also worth addressing here the transparency of the heating system to the matrix so that conduction will be the sole mode of heat transfer from fibre to the polymer matrix. Therefore, it is worth thoroughly investigating the performance of these heating mechanisms in consolidation. This will assist in fully grasping the significance and efficiency of the heat input as it concerns the influence on the quality of the final product. In addition, it would be beneficial to evaluate the effect of a surface finish of the prepreg tapes (resin-rich areas, surface roughness, etc.) on their behaviour and the interaction between the emitted heat energy and the surface finish on the general performance of the final product. These studies will enable an improved optimization of the process as it regards the temperature distribution profiles which significantly influence many of the mechanisms behind the melt fusion fabrication process.

For heating systems, there has been a growing trend of using two heating sources simultaneously instead of a single source [101]. Tierney and Gillespie [80, 81] suggested that the inclusion of pre-heating systems in the process will be isolated from compaction but will assist as the first stage of adhesion between the layers, this would help in preventing any future defects based on the material preparation (fibre misalignment, poor tension for incoming tapes, etc.). This has been supported by Barasinski et al. [102] with the major heat source which was laser-based acting between a two-roller compaction setup. The addition of the diode laser type NIR (near-infrared) has enabled utilization with a greater focal length than the CO_2 lasers from 127 to 250 mm. This makes diode laser the most applied solution but is limited by the lack of homogenous heat intensity distribution [103]. However, this can be mitigated by homogenizers where homogenization can be done by varying options i.e., waveguides, beam superposition, and a set of micro-optical lenses. CO_2 can be useful as an option for heating uncoloured surfaces of glass fibre-reinforced polymers or unreinforced polymers [104]. This concept is beneficial to fixing the issues linked to the first/substrate layers or where sheets are to be used as functional sheets and for hybrid parts development.

For complex regions which include curved surfaces, the major issue is overheating, which is linked to the position of the laser based on the distance to the plies, and it is common for irradiation to occur because of the connection between the supplied power and the irradiated surface. The surface size reduction generates more irradiation at a maintained power level. These advantages also have a direct implication on the influence of the tendency for overheating encountered at the output or underheating from laser inputs. Contrastingly, this system still has homogenization despite the laser beam issues and this necessitates the positioning of the system very close to the nip point and limits the right positioning of the control and temperature monitoring systems.

2.3.2 Temperature Distribution

Additionally, the energy input ascertains the temperature distribution in the manufacturing area. At the highest processing speed, a directional temperature gradient occurs when the maximum temperature is at the outer layer of the incoming tape at the nip region inlet. To obtain the best quality, it is recommended that the temperature should not surpass the matrix degradation temperature. In terms of how materials react to heating, the tape melting surfaces are normally rough, but this vanishes during melting, and deformation occurs during intimate contact. As intimate contact continues, curing is initiated and advances. The adhesion mechanism between the layers of the composite structures can only be analysed when two key factors are addressed. These are firstly the mechanisms responsible for chain movement and the elimination of surface roughness in the feed material which enables the movement of the polymer chains. Healing occurs from the diffusion of the polymer chains at any spot of intimate contact. Increased temperature (disregarding pressure) propels healing, which is estimated to be when $T > Tg$, irrespective of the consolidation. Furthermore, a higher temperature which is high as the degradation temperature propels faster healing. It has been established that polymer degradation occurs when the tape is subjected to prolonged excessive temperatures during lay-up. This degradation severely affects the performance and properties of the final product by reducing the modulus of the material and increasing in T_g of the matrix [105]. Nixon-Pearson et al. [106] has shown that void content is greater in room temperature debulking and reduces with the elevation of debulking temperature and consolidation by maintaining the conditions with hot debulking. The interlayer regions are key void elimination pathways. Crystallization is another major stage in the curing process as certain aspects of the crystallization phase can influence mechanical properties. When a material cools from melting, thermoplastics recrystallize into a partially ordered crystalline structure termed lamellae, roughly 10-20 nm thick and created from polymer chain folding. For bulk polymers, lamellae expand radially from the nucleation point, which forms spherical crystalline zones termed spherulites, and where fibre is present, there is a tendency for phenomena such as trans crystallization to occur.

The influence of thermal degradation on the consolidation process of the material and how it is applied to in situ consolidation process of thermoplastics is also essential. Thermal degradation as pertains to polymer is defined as a process that occurs at elevated temperatures or from heat action, and consequently, there is the irreversible loss of electrical, physical, or mechanical properties [107]. On this note, Fink et al. [108] performed interlaminar shear strength (ILSS) analysis for test samples manufactured in varying heat conditions. It was concluded that the two dominant mechanisms that control the ILSS are bonding within the layers and degradation. At elevated temperature (700–900 °C) subjected to poly ether ketone ketone (PEKK) using a gas torch within a quick deposition rate of 20 and 40 mm/s which was subsequently reconsolidated in a hot press for 30 min at 370 °C subjected to 0.70 MPa pressure for the purpose of improving the consolidation and bond strength. The effect of degradation is induced into the polymer, which forms voids at a surface that is not corrected by successive layups and causes strength reduction in the final part. Microscopic examination revealed higher void content at the two ends of the temperature intervals where at the lower temperature it is associated with weak bonding and at high temperatures with long resident time affiliated to degradation. It is admissible that further experiments are required to resolve and provide a better understanding of the influence of thermal degradation on fibre-reinforced thermoplastic composite structures from manufacturing onset in automated processes.

2.3.3 Device Temperature

For the device temperature, it is understood that void volume decreases with slower consolidation speed which is turned over when the component temperature approaches the melting temperature of the matrix. Where the temperature is low, it is expected that the device will act as a heat sink. This results in high viscosity that hampers polymer chain movement and reduces the degree of bonding, which raises a necessity for reducing the layup speed. Contrastingly, at high device temperature, an improved degree of bonding may be obtained even at a speed of 10 m/min. Also, an increase in porosity/void level is enabled by a longer heating length. Nevertheless, there is also an improvement in the degree of bonding, and this implies that the layup speed can be taken higher. There exists a direct relationship between the heating length and the heat time which is the speed of consolidating the prepregs.

2.4 Layup Process, Compaction Force, and Tape Laying Speed

Maintaining a low level of defects is critical for high-performing structures. The key parameters that influence the manufacturing at three different stages (start, process, and finish) of the lay-up process [57] and inappropriate selection of these parameters may cause defect formation. Hence, a sound understanding of these variables and their influences results in quality enhancement and optimization of the manufacturing process [109]. In addition, considering the intricacies involved with the layup process, Khan et al. [77] and Martin et al. [110] reported on the various conditions or parameters of the consolidation that affects the porosity level and degree of bonding between the layers. The thermoplastic-based prepregs require controlled storage conditions either stored at room temperature or frozen respectively which can impact their performance. Also, the number of layers in a layer can be classified as high by the occurrence of a double effect. Herein, the top layers are significantly isolated from the heat sink tool, but the bottom layers receive more of the consolidation and re-consolidation stages–hence, great heat is generated, and this has an influence on the increase of pore sizes. After ward, a post-treatment procedure for mostly surface property enhancements can be carried out [73].

It is also expected that the degree of bonding increases with high compaction force while the void content decreases. It should significantly influence the layup speed where increasing speed raises the need for more force. For the lay-up speed consideration, an increase in both the speed and force should cause a decline in the porosity/void level. However, despite the degree of bonding increasing with force, it will reduce with increasing speed. Squeeze flow covers the fibre/polymer flow, as common with thermoplastics as a basis of pressure distribution over the tape to yield the decrease in height and expands in width, this is shrinkage on cooling attributed to the coefficient of thermal expansion (CTE). This is followed by a decrease in void content [73]. The key mechanism for interlayer void reduction is gas compression during consolidation, other means of void reduction are coalescing and the occurrence of migration and bubbles which is illustrated in Fig. 6b.

Qureshi et al. [111] studied the lay-up speed on the influence of tape laying speed on the ILSS at a varying set of lay-up speeds of 57, 68, 73, 82, and 95 mm/s. It was established that the low lay-up speed (57 mm/s) causes a high ILSS (50.58 MPa) by providing more time and increased heat flow intensity as well as the polymer diffusion on the interface. However, higher temperatures cause polymer degradation and consequently reduce the ILSS. Pitchumani et al. [105] investigated the lay-up speed effects and a number of layers/plies bonded, the extent of degradation, void formation, and compaction of composites. They deduced that the bonding quality improves with an increase in the number of plies at lower lay-up speeds until a maximum value (20-30 mm/s) is reached and from there it starts decreasing at high lay-up speeds. However, lay-up speed increment is accompanied by a decrease in bonding quality and void formation. This is attributed to insufficient timing for the matrix to melt at the interface. Noteworthy, lay-up speed increase creates a decrease in temperature exposure time which reduces the extent of degradation. However, when the number of plies increases ($N \geq 4$), more heat is accumulated in the plies causing a rise in the degradation level within the part. An earlier study by Romagna et al. [112] indicated that increasing the lay-up speed during winding simultaneously results in a reduced energy flux coming into the nip point causing the plausibility of the matrix to totally melt.

3 Prevalent TCP Defects and the Impact of the Defects on Composite Mechanical Performance

The manufacturing induced defects and the factor behind its appearance is emphasized here. Also, the failure mechanism that leads to in-service defects is identified. An attempt to address the relationship of the common principles between the materials, manufacturing, and failure mechanisms is also highlighted.

3.1 Identification of TCP Defects

The objective of any composite manufacturing process especially for TCP is to achieve uniform quality (low void content, degree of bonding between layers, and minimal warpage) across the structure [51]. The generic meaning of defects can be defined as any element that deviates from the uniform or ideal structure [113]. It has already been established here that through manufacturing/processing techniques, defects are induced into the structure at the early stage [50, 51, 114]. Despite the advancements attained in the manufacturing of composite, there is a possibility that microscopic or macroscopic scaled defects may be induced during TCP manufacturing. Generally, in composite structures such as TCP, these defects and fracture modes entail both microscopic and macroscopic dimensions as outlined in Fig. 7.

Besides using their sizes, another practical method for categorizing these defects is by grouping them into fibre, matrix, and interface defects [50]. Examples of fibre defects are irregular fibre distribution or tow distortions, waviness, misalignment, and fibre breakage; for matrix defect it concerns void formation and incomplete curing and for the defects at the interface they are poor bonding in areas between the layers (delamination) or on the fibre surface discussed in the following sections.

3.1.1 Fibre Based Defects

To expound on the categorization which includes fibre defects, there is an assumption that fibres used in TCP are parallel, straight, or oriented in the required directions. There are no

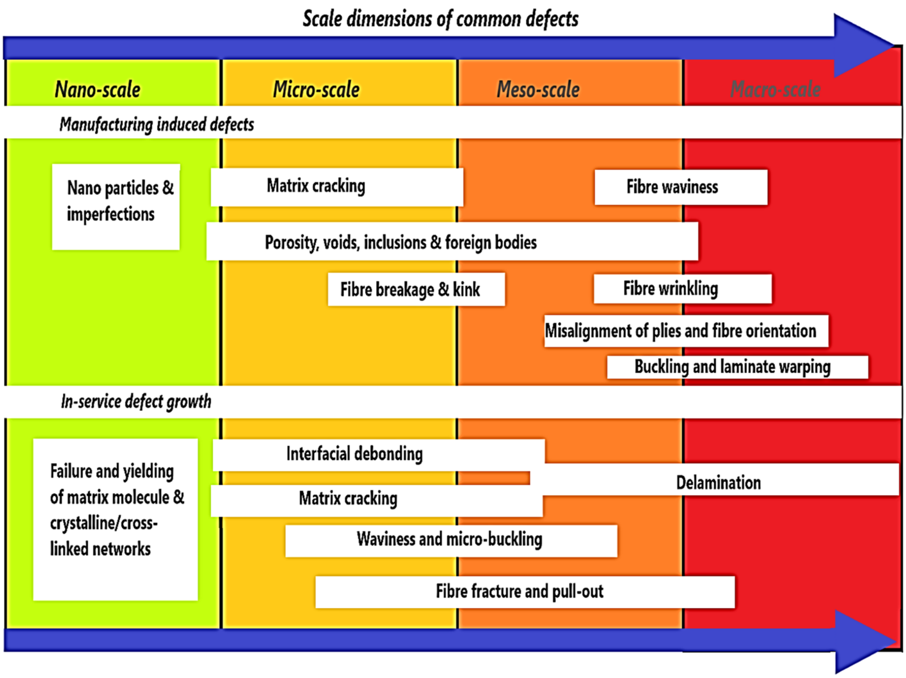


Fig. 7 Manufacturing induced defects and in-service damage mechanism of composites and their potential scale dimensions

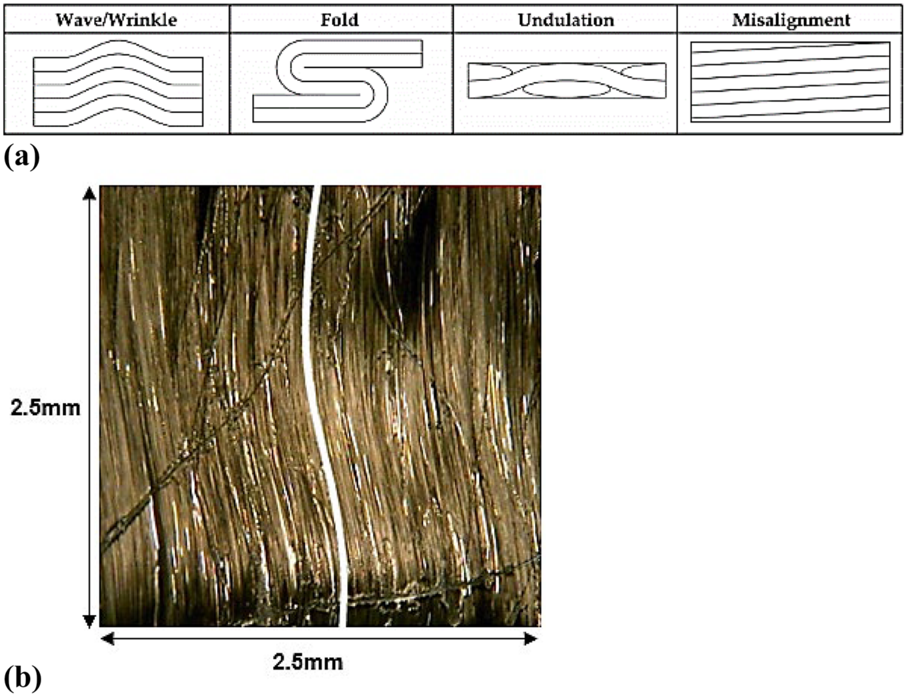


Fig. 8 Illustration of the **a** general distinction on the deviations from the planned fibre orientation which includes waves/wrinkle, folds, undulation, and misalignments [115] **b** nature of fibre misalignment in a basic prepreg [116]

generally approved terms and consistent definition that differentiates folds, misalignments, undulations, and wrinkles as depicted in Fig. 8a.

For clarification, it is useful to provide a basic definition for the reader. Fibre/ply waviness or wrinkling are the most observed fibre defects from the effect of manufacturing fibre reinforced polymer composite parts which result in a decrease in mechanical performance. Fibre waviness can be defined as fibre deviations or wave formed ply from a straight alignment across a unidirectional ply. This can form unwanted manufacturing defect that commonly happens during the consolidation or cure phase. When out of plane fibre waviness occurs from issues with stability when the ply is loaded during subjection to compression, this can also be termed fibre buckling. Wave plies can emerge in random locations and shapes, this defect can be classified as either in-bound or out-band waves. However, Nelson et al. [97] has stated that both wave forms exhibit similar strength degradations pattern.

Thor et al. [115] defined fold as a particular form of waviness with a maximum deflection of the fibre misalignment where there is a contact of the layers with itself. Undulations are minute-sized fibre misalignments at the microscale as a type of wave that can be observed in various prepreg manufacturing processes. As a result of undulations, fibres such as woven fabrics generally exhibit reduced stiffness and varying damage behaviour in comparison to UD layers [117–119]. Hence, fibre misalignments can be broadly described as an angular deviation from the planned, nominal fibre directions and cause a mismatch to the designed fibre path. Nonetheless, many reports use the term fibre misalignment as a generic term for wrinkles, undulations, and folds [115, 120]. However, deviations from waviness and misalignment can decrease the original properties, most especially the compression stiffness and strength, which results in restrictions in the design limiting load performance. A depiction of the nature of misalignment that can be seen in the typical as-ready unidirectional prepreg is provided in Fig. 8b.

It is challenging to manufacture composite materials that are detect-free due to process-induced variations which cause differences in the final geometry of the part from the mould shape. Several conditions enable the occurrences of defects, and they are mainly the material characteristics and mould features [121]. Geometrical differences in moulded composite parts such as being flat or curved remain the key challenge for manufacturing the composite components. An increase in the complexities also increases the number and variety of plausible defects [122] that can be grouped as the effects of the induced waviness, their origins, and formation.

Effect of Mechanical Load and Impregnated Fibre Reinforcement Behaviour Due to the anisotropic behaviour of fibre reinforced polymer, the material behaviour differs from that of isotropic materials. For isotropic materials, only normal stresses can cause normal strains and only shear stresses create shear strains. For the cured/consolidated fibre reinforced polymer composite structure, the stress for decoupling is only possible when subjected to specific conditions where symmetries are included in the stacking sequence [123].

In most cases for polymer matrices, there is a relationship of the moments to mid-plane strains, occupied curvatures, cross-sectional forces, and hence the coupling of bending, extensional, twisting, and shear behaviour. However, during processing, the matrix is either absent for dry reinforcements or melted for melting processed thermoplastics. Another source of waviness-induced defects is from mechanical deformation of layers due to manual handling of the prepregs, movement of consolidation rollers, and post-curing tools. It has been established that misalignment in general, which includes fibre waviness particularly is initiated from labour-intensive prepreg placement into the mould before the heating and curing phase. Fibre waviness can also emerge from the consolidation phase where the prepreg is compressed at this stage which induces tension forces around the bends and curvatures most especially in huge geometrically complex parts or when the plies are moved by the rollers from the designed position [115]. Dong [124] reported that the possibility of fibre waviness occurs from a marginally oversized prepreg being forced on the mould cavity. However, this is not regarded as a manufacturing/processing effect, rather it is more of a design challenge and can be corrected by modifying the ply size.

Effect of Differences in Path Length For micro/meso-scaled deformation at the material level, it is understood that bent continuous fibre reinforcements form waviness due to path length differences between the lower and upper sides of the ply [116]. This effect is regarded as being caused at the micro/meso scale of the material level. Furthermore, waviness can be formed if the ability of the plies to slip against each other is very low or perhaps limited. This effect can be mitigated through temperature control, cure rate, and the distance from the nip point to the post-cure phase where the needed slip between the plies must be satisfied [125]. Also, plausible global deformation by drape on joggled geometries and double-curved surfaces at the structural level can form path differences on the reinforcement and the geometric path where the position on the surface can differ tremendously, hence resulting in the obvious risk of layer wrinkling because of the path distance difference at the macro scale structural level. This drape refers to the ability of the fibre

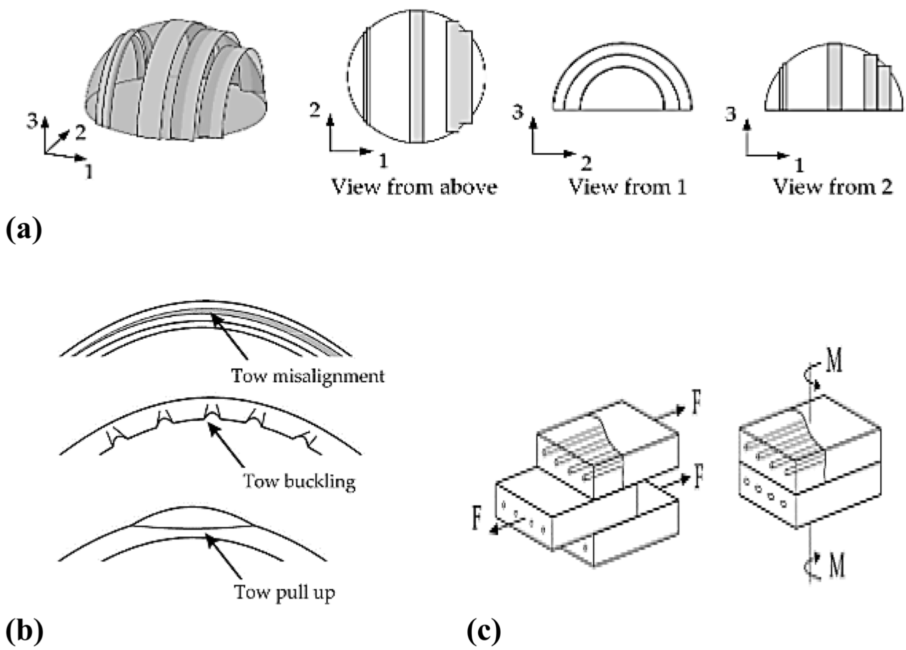


Fig. 9 **a** Path length differences between tow edges on a double curved or hemispherical surface **b** Schematic illustration of the tow steering defects resulting in out-plane fibre **c** The interplay formation mechanisms which include inter laminar slip and inter laminar shear [115]

to stick to the moulded surface without out-of-plane buckling, fibre movement, or distortion. The level of complexity for the finished part significantly impacts the fibre waviness occurrence. Potter et al. [116] stated that the distinctions in path length can create noticeable fibre waviness. Figure 9a presents a schematic illustration of path length differences between tow edges on a hemispherical surface.

Furthermore, Thor et al. [115] noted that wrinkles initiated from the pre-stacked prepregs can be partially reduced through the application of higher consolidation pressure during successive autoclave curing. Also, for parts with notable double curvature that require a large area draped reinforcement layer, selection of fibre with narrow instead of wide tows decreases the fibre waviness level.

For AFP, the automated controlled prepreg tows/tapes are placed along the pre-designed path on a three-dimensional tool surface by applying temperature and pressure. As a result of the path steering of the device head, the layers are then optimally aligned in accordance with a pre-designed load path. However, various defects can emerge which include bridges, gaps between the placed tows/tapes, both out-plane or in-plane buckling of tape, or tape lifting on the external tape with a narrowing radius. Basically, defect formation is a function of the selected steering radius during the design phase. Figure 9b provides a schematic illustration of the tow steering defects. While steering, the tape bends the in-plane surface which makes the fibre on the outer edge to be subjected to tension and fibre across the inner edge to be subjected to compression. Another element is the consolidation in external radii, tight regions, and tapered or stepped plies as the consolidation of considerable thick parts with internally tight geometries can push the plies to move to the corner direction and create wrinkles because of the direct pressure acting at the layup edge. This effect is based on the length of the part as it impacts the probability of ply slippage and hence can be covered in the manufacturing planning and design decisions. Ply debulking over the outer radius during the consolidation phase enables the exact fit on the tool geometry and enhances the adhesion between the layers. Consequently, the outermost plies are pushed into a tighter geometry that results in additional length.

Effect of Non-uniform Pressure Distribution There is the possibility that indentations will occur during spot heating of thermoplastic prepreg stacks, and in the form of wavy layers due to increased contact pressure of the consolidating device which causes the material to exhibit a softening behaviour due to elevated temperatures as in Fig. 9b. The ply stacks are mainly arranged at the nip point and further processed in the consolidation and cure stage. Fischer et al. [126] noted that in the following consolidation, the compacted part has a distinct imprint on the top which makes any disrupted fibre clearly visible. It was recommended that the nip point should be positioned in non-critical regions of the part. Ply bridging is also an effect of poor draping when the reinforcement does not have contact with the mould surface possibly due to inadequate layup and debulking. Bridging is sometimes inevitable and induces wrinkling. At high consolidation pressures and low resin viscosities, matrix migration can be noticed in the bridged regions along the ply radii when the resin is pressed/squeezed into the external area.

Effect of the Interaction between Ply to Ply and the Tool to Ply The interactions of ply to ply and tool to ply can be expressed through viscous friction laws. The sliding between the ply and tool along with ply and ply is influenced at their interface by the coefficient of friction [127]. Interaction between the operating tool and component has a maximum impact on the geometrical uniqueness of the composite part [128]. Out of plane of fibre and in-plane buckling of the fibre tows can occur from the high frictional force. Factors that affect the friction coefficients are processing temperature, fibre tow surface, and mould surface roughness which generates a change in viscosity. Stickiness or tack, which is the ability of a partially cured prepreg layer to attach to the mould surface alongside another prepreg layer without creating chemical bonds, is another essential property of prepregs. Prepregs with minute resin on the surfaces have reduced tack and can require heating to enhance the tack during layup. However, when the surface is resin rich while the inner resin is lower, the prepreg can split in the centre during the layup process.

As noted earlier on, the wave formations rely on frictional behaviour between the plies. At low friction, the extra length can diminish into the remaining part through shearing in the interface of the layer. At the inception stage of the curing process, the moduli and shear of the resin are extremely low [129]. This can possibly be reduced with elevated temperature and lowered viscosity at the first stage, which enables a certain level of ply movement to appear prior to increasing the cross-linking for the material properties. The two key inter-ply formation mechanisms are inter-laminar shear and inter-laminar slip which is illustrated in Fig. 9c. Inter-laminar slip connotes the relative shear movement of two adjoining plies. This occurs when the layer slides or slips relatively to the adjacent layer when the flat prepreg stack deforms on a single curved surface. For a ply stack that deforms on a double-curved surface, the mechanism for intra-ply shearing becomes prevalent. This is an in-plane shearing mechanism where the fibres move against each other amongst each ply.

There is also a CTE mismatch, as the longitudinal stiffness of unidirectional composites is extremely greater than the transverse stiffness and the transverse CTE is much lower than the longitudinal CTE [124]. Although the anisotropic behaviour of composite materials is an advantage from a structural perspective, it can also be the key reason for process-induced deformations. For high-performance composite material, curing occurs at high temperatures, and the cool-down process or rate in particular causes a massive CTE mismatch. Also, as earlier stated, the residual stresses can occur because of the CTE difference between matrix and fibre. The differences between the reinforcement and coefficient thermal expansion create contact strains and stress leading to tool heating. These elevated stress and strain gradients penetrate the through-thickness of the part and generate a warping effect when the part is removed from mould. Often, resin shrinkage can also result in dimensional changes in the part because of the interaction between the tool and part. Preferably, the coefficient of thermal expansion should correspond to the proper moulding of fibre reinforced polymer parts which often becomes an unavoidable operation because it involves increased cost and time.

Effect of the Layup Sequence, Foreign Objects, and Fabrication Process Techniques Basically, the lay-up sequence has a huge impact on the formation and generation of deformations. When separate plies are fused during layup, gaps and overlaps can plausibly occur. However, gaps and overlaps are mostly synonymous with automated manufacturing processes and their steering techniques. During the local tape laying placement process with consideration of the load path, the produced part mainly comprises several overlaps and gaps which can be of varying sizes and complicated combinations [130]. With the overlap of plies, gaps and humps are created which push the positioned plies into any gaps during the consolidation phase both resulting in fibre waviness and influencing the mechanical properties of the final part.

Another effect of the layup sequence is the ply drop in tapered parts where ply drops here refer to ply terminations. Ply terminations for most high-performing composites are needed within the parts with several plies between two adjoining areas of the part and this necessitates local reinforcement application. However, Hart-Smith [131] reported that for inadequately created ply drop areas, the consolidation of these areas can result in added fibre waviness which subsequently will impede the structural properties more than a set of properly created external ply drops. Variations in path thickness produce additional ply length, which diminishes either through intraply slipping or when the interlayer friction is significantly higher, from an out-of-plane movement that accounts for the added length. Steeves and Fleck [132] reported on the compressive strength of composites with terminated internal plies. They noted that the first failure mode was observed to be fibre microbuckling, which is guided by the induced fibre waviness of longitudinal fibre in the presence of the ply drop.

In several conditions, foreign objects can be purposely incorporated into the composite material such as metal pins for bonding parts, sensors for structural health monitoring, or inserts. This can then obstruct the fibre orientation which unavoidably causes local fibre waviness. Foreign objects can also be integrated into the composite material unintentionally such as tools (knife blades) and release film which can be categorized as defects during ply sequencing [115, 133]. These defects cause fibre waviness which is similar to the intentionally embedded objects, and all this can be mitigated through strict compliance with rigorous quality control and processing instructions.

It has been established that the geometry, size, and type of composite part and the range of application determine the selection of the suitable manufacturing process. It is essential to establish the manufacturing grade with the required strength based on the allowable defect limits [50]. Furthermore, there is a significant scrap rate during the manufacturing process of the part. With the varying manufacturing techniques which include manual and automated for the prepregs, large gaps and overlaps can possibly occur due to the geometry of mould used in the process. An unfilled, unidentified, and partially filled gap produces resin-rich regions which cause fibre waviness [122]. These major parameters serve as sources for fibre waviness formation that influence the manufacturing process.

For filament winding processes, fibre waviness is a major manufacturing effect of this process. However, the determination of the mechanism behind the formation of fibre waviness remains slightly unclear. There is a possibility that fibre waviness in filament winding processes can emerge from poor winding tension [127], local fibre micro buckling generated from the compression load derived through the shrinkage of material from consolidation using metal tools [134], or because of the volumetric variations during resin bleed-out for thick wound composite structures [135–137].

In the case of pultrusion which manufactures composites in profiles in a constant cross-section. The cooling and thermal history combined with extremely non-linear resin phase transitions which are viscous to rubbery to glass, makes the manufacturing process challenging to control and massively influences the quality of the end composite part. The matrix undergoes significant changes in the material properties during phase transitions, these critical properties are the elastic modulus and thermal expansion [138]. Some of the commonly known defects induced through this technique by stress and shape distortions are wrinkles, fibre breaking, and fibre shifting, which are all forms of fibre misalignments that can lower the structural properties of the pultruded part [127]. Elhajjar et al. [139] explained that random in-plane waviness, which is continuously distributed, can emerge during pultrusion because of locally inadequate tow tension from the feeding spool as illustrated in Fig. 10a.

Effects of Consolidation, Temperature Gradient, and Fibre Mismatch For parts that require a specific thickness, it is essential to apply external pressure or compression over the part to sustain the ply thickness, which is termed compaction or consolidation [140]. The combination of thermoplastic materials with unidirectional prepreg has the maximum inter-ply friction through the thickness. An additional increase in compaction also elevates the friction that creates out-of-plane waviness. Moreover, in the formation conditions of external radius, the external ply is forced to form shapes as the layer shear or slips over each other the additional span can be integrated. If the process resistance is high, then the layers form wrinkles with small amplitudes, as depicted in Fig. 10b [116]. The manufactured composite parts experience residual stresses in varying locations because of the differences in thermal expansion coefficients of the components because of the different thermal properties of the polymer matrix and fibre. At the laminate level, these thermal property differences create stress variations across the thickness. This difference between the thickness and in-plane lamina coefficient of thermal expansion forms thermoplastic distortions which subsequently cause fibre waviness [116].

When continuous and straight fibres are exposed to curved regions of the composite part, they may buckle to create a wavy region. Typical commercial prepregs have a small amount of wavelength and degree of misalignment. Also, when these prepregs are exposed to curved parts, it is expected that the overall misalignment increases and this forms severe wrinkling. For three-dimensional geometries, there are endless ways to drape the prepregs. The product of draping relies on the start and finish points. These varying drape patterns are expected to end differently with varying forms of misalignment and waste of prepregs. Pandey and Sun [141] described the two key mechanisms of wrinkling formations for

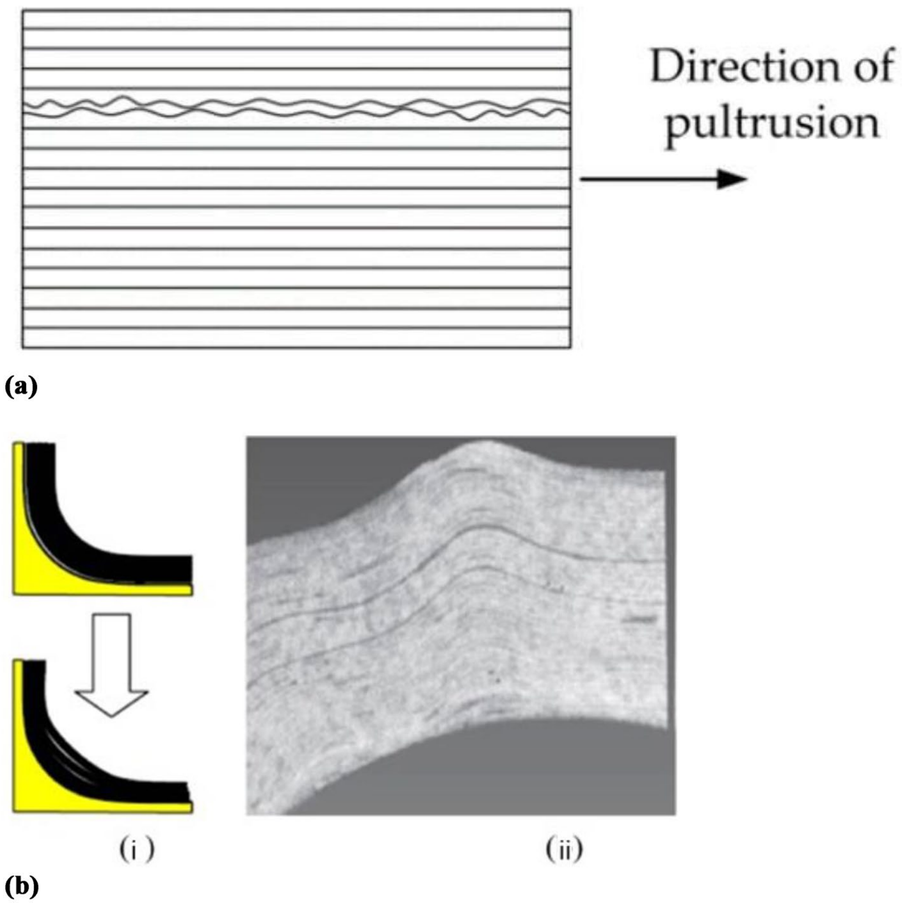


Fig. 10 **a** Random waviness occurrence in the direction of pultrusion from poor tow tension **b** Consolidation of plies on a small bend radius (i) schematic illustration of wrinkle formation on consolidated plies on mould (top; before debulking, bottom; after debulking) (ii) CT scan of wrinkle [50]

composite materials which are buckled and straight layers. For the buckled layer approach, it was observed that the difference was the potential energy being a function of variation in the onset of the wrinkles formed. While for the straight layer approach, flat fibre reinforced laminates were considered with regard to the wrinkle length, and a relationship between the wrinkle length and load was found using eigenvalues. Based on the restrictions of automated tape placement units in placing small heads which creates waviness, Beakou et al. [142] recommended defining the critical buckling load and the minimal turning/steering radius to prevent tow wrinkling formations to resolve this issue for a circular fibre path. However, it should be done carefully to prevent stretching of the external fibre tow to avoid lateral compressive stresses which cause transverse buckling. It is expected that applying this approach will precisely provide the minimal turn radius that avoids the induction of tow wrinkling for a specified compaction force and nominal stiffness. Besides, where the orientation of the fibres is longitudinally in a composite is wavy, local misalignments are

Fig. 11 Void between the fibre layers in a composite is highlighted [148]

created along the load axis. Shear stresses are induced as a result, and this is a prevalent rationale behind compressive failure.

Generally, it is expected that to reduce fibre misalignment during consolidation, the individual fibres should be tensioned. Other considerations for preventing fibre misalignments within a fibre-reinforced polymer structure have been studied [120, 143, 144]. Unlike thermosets, thermoplastic-based polymer composites have proven to display enhanced qualities in regards to fibre distribution within the matrix as well as fibre misalignment. This is attributed to the crystallization of polymers occurring when the fibre is subjected to tension. Although the oven treatment of thermoplastic composites using optimized parameters (e.g. at pressure and temperature greater than polymer melt temperature) indicated improvements in the fibre distribution, there is a likelihood of degradation in the fibre misalignment. This is due to the melting of the polymer matrix at the oven conditions and also enables consolidation while separate fibres are not hindered [120]. Another strategy is the pre-forming technique which is a prevalent phase during manufacturing where each fibre orientation is individually controlled to avert fibre misalignments [144]. Noteworthy, despite the objective of optimizing the composite manufacturing process being defect reduction and strength improvement, lower misalignments can also generate an extensively severe failure when subjected to longitudinal compression as the ply is exposed to a higher load drop which is followed by a rapid fibre movement [143].

3.1.2 Matrix-based Defects

Voids Formation and Defects For matrix defects, insufficient matrix cooling and voids are the most prevalent and can be discovered in almost all forms of polymer matrix composite structures irrespective of the manufacturing technique involved. Voids which can be described as unfilled regions within the fibre, polymer matrix, and their formation can partially be mitigated by the manufacturing processing factors which include the matrix viscosity, consolidation pressure, and cooling temperature [51]. The influence of voids is based on the significant effect they have on a broad range of composite properties and mechanisms that causes structural failure alongside understanding the high probability of their formation in various manufacturing techniques.

Voids in composites are highly significant and hence are the most studied manufacturing defect for composite parts. A void can be described as an unplanned feature present in most composite materials. They are essentially unfilled pores in the material that are empty spaces occupied with gas rather than solid material (Fig. 11). The formation and evolution of voids during the manufacturing of composite parts are dissimilar for all manufacturing techniques based on the variations in rheological and thermodynamic circumstances that occur in these processes [145]. Normally, the voids are formed due to imperfections during the manufacturing and processing phase which are undesirable as they can possibly decrease the mechanical properties alongside the life span of the finished product. This defect can serve as a crack nucleation site and if the crack propagates, can display unpredictable behaviours which may even cause the devastating failure of the composite structure. During the impregnation of the tapes, voids can be readily formed within the tape as the fibres will not entirely be covered for certain regions and this void type is termed intralaminar voids [146]. Hence, Intra laminar voids are generated between fibres that possess a great aspect (length/width) ratio mostly in resin-rich regions [147].

Voids are amongst the most prevalent defects in composite parts and are well known to degrade their mechanical performance. Hence, void content measurement is a method used in both ascertaining the quality of the composite part and determining their approval. Presently, components that need the best quality are manufactured at high processing pressures and temperatures. The curing phase has been shown to be minimally affected by environmental parameters such as humidity [149].

Based on the polymer matrix and the form of manufacturing technique, a few varying void types can appear in a composite material. Specifically, voids can likely be formed from viscous matrix resins in the final composite due to the difficulty of the resin to penetrate the region between the fibre layers, particularly for closely packed fibres as depicted in Fig. 11. Where the matrix does not penetrate the region between the fibres, the air-filled is never squeezed out and replaced by the resin. Rather, the air regions are retained and cause severe void challenges. Also, certain basic manufacturing will likely contribute to void formation in the final part. An instance is that a lower curing temperature may not enable a complete degassing/debulking to happen, instead, if the temperature is elevated then gelation rapidly occurs which gives the gas/air little time to diffuse from the material. For both conditions, the air or gas pockets left in the material transform into voids and can impede its mechanical properties [148].

To ensure that the manufactured part has low void content irrespective of the technique and the effects of the manufacturing process variables, Kardos et al. [150] developed a model to predict the void content and final void diameters in composite parts provided the moisture content and processing pressure is identified, the processing pressure not being an input parameter posed a challenge to this model. Also, moisture content is another vital factor to consider prior to fabrication. Absorbed moisture into the composite can introduce a plasticization effect on the matrix and lowers the glass transition temperature which can cause degradation of the material and induces faster ageing. When the material is exposed to hot humid conditions, moisture diffuses through the matrix, fibre, and matrix-fibre interface. Here the plasticization effect alters the mechanical and thermal properties of the matrix by elevating the elongation to break at ambient temperature, lowering the temperature which makes the material prone to significant deformation from little forces, increase in toughness at even the lowest in-service temperature, and reduction in rigidity at ambient temperature. Plasticization will likely occur by either adding a comonomer into the polymer matrix which increases the chain flexibility and decreases the crystallinity or compounding the polymer to a low molecular weight compound or some other polymer [151]. Later on, Anderson and Altan [149] determined the effect of processing factors and resin moisture content on void formations in fibre-reinforced composites. It was learned that a prepreg exposed to humid conditions will quickly attain its saturated moisture content at the level of humidity. It was also discerned that the void contents of the produced part slightly reduce with an increase in the processing pressure, regardless of original moisture content and this does not match the previous model. Therefore, through this means, the model is improved by accounting for the variation between the resin pressure and processing along with the time-reliant moisture absorption by the prepreg. Consequently, the reduced void content was due to the fibre bed possessing a massive share of the applied pressure during manufacturing, and the voids are entrapped inside the part, an area that warrants further research investigations to develop models to predict void contents of consolidated composites produced with varying fibres and resin systems [149].

Recently, interest in thermoplastic composites has risen due to their greater features which include longer time storage, improved impact properties, ease of recycling, and shorter processing times. The manufacturing process needs a heating method, either in a hot mould which is isothermal processing, or straight before the final moulding stage with the combined use of a cooling tool and heat source which is a non-isothermal process. For instance, laser-assisted ATP is among the non-isothermal processes that utilize laser as the heat source for matrix melting at the same time the tapes are attached to the tool and then consolidated from a compaction roller. For composite manufacturing, if both the application time and pressure are not optimized, voids could be formed in the part. The void occurring can decrease the longitudinal compressive, transverse tensile, and ILSS. Furthermore, to induce local stress concentrations, with a consistent severe degradation of stiffness and strength in-service. For industrial applications, the void content of 5% can be accepted based on how it is used [120].

For automated manufacturing using prepregs unlike other methods such as liquid composite moulding (LCM), void formation with this technique is mainly studied at the placement and cure phase. However, similar to fibre waviness the mechanisms for void formation and evolution during the cure of prepreg composites are still yet to be fully known [152]. Additionally, intra-laminar voids are also a major challenge in prepregs automation which does not occur for LCM. The key contributors to voids in prepreg composites are air entrapment either during inter-laminar void (laying up) [153, 154] or intra-laminar void (impregnation) [155], moisture absorbed by the resin [150], and volatiles emerging from the resin during cure [155]. The latter contributors were previously the key source in prepregs, however current prepregs have extremely minute moisture and volatile contents which makes mechanical air entrapment the prime mechanism [156].

Earlier impregnation and the volatile level in the resin are the parameters that can be mitigated in prepreg production and will reduce final voidage. The controlling factor in composite manufacturing remains the conditioning of the prepregs, laying up a procedure that covers mitigating the extent of entrapment between plies and the cure conditions. Although it will be essential to study the different manufacturing technologies based on their differences in their lay-up and curing processes, this study will be streamlined with an emphasis on automated manufacturing techniques.

As earlier stated on prepregs, current prepregs have significantly low moisture and volatile content. Hence, the final voidage is mainly controlled through entrapped air during lay-up and the consolidation pressure and temperature used to collapse the entrapped voids [157]. The automated prepreg uses a distinct stacking approach and often in situ consolidation and this makes investigating the manufacturing technique through the formation of voids appealing. The lay-ups may also be consolidated in autoclave which suits in-situ consolidation during lay-up, and this is based on the material type and manufacturing specifications. Noteworthy, void formation through this technique is influenced by a defect present in the tape laying due to imprecise laid tapes i.e., overlaps (areas of increased local

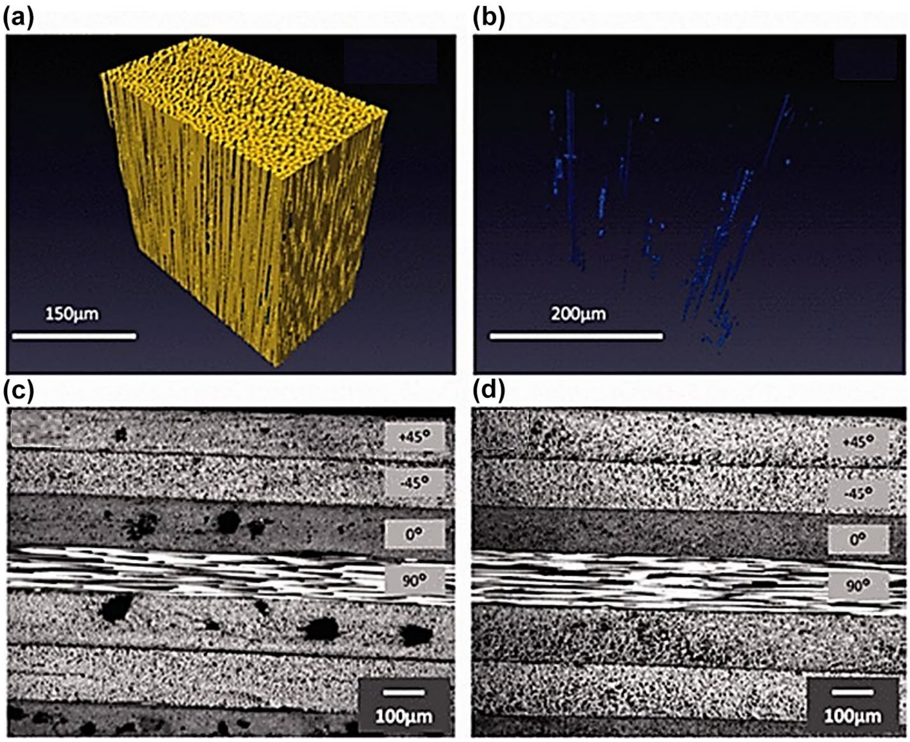


Fig. 12 Micro-CT images of unconsolidated ATP carbon/PEEK prepreg (UD), illustrating **a** intra-tape voids (blue) and carbon fibres (yellow), **b** isolated elongated voids along fibre direction. Increased voids in micrographs of the consolidated sample were observed and **c** for laser-assisted and **d** consolidated in autoclave [158]

fibre volume fraction on the overlapping tape boundaries) and gaps (matrix space between tapes). The steps involved with using ATP for thermoplastic prepregs are heat application, initiation of intimate contact between overlying tapes, inter laminar voids removal, interfacial healing, consolidation, and squeeze flow from the compaction roller force applied to reduce intra laminar voids, formation of voids from elevated temperatures and matrix degradation [81]. The quality of the final part is examined primarily with the interfacial healing and voidage of the final product.

Contrastingly to autoclave processing of semi-crystalline thermoplastic composites, in-situ consolidation processes have a narrow processing window when increased pressure and temperature are applied. Hence, reptation of polymer chains across the ply interface, macroscopic resin flow, and several void reduction methods such as migration, bubbling, compression, and coalescence which are common for autoclave, sparingly occur for in-situ consolidation processes. As a result, prepreg variables which include the degree of crystallinity, fibre volume fraction, dimensional tolerance, and void content now become the vital parameters for defining the quality of the semi-crystalline thermoplastic composite produced through automated in-situ consolidation. Furthermore, the various heat source for automated manufacturing such as laser, infra-red or hot gas plays a huge role [158].

Comer et al. [158] derived through micro-CT that voids from unconsolidated carbon/PEEK prepreg are greatly stretched in the fibre direction as depicted in Fig. 12a and b. It was also discovered that there were more voids in the laser-assisted ATP whereby the mechanism here combines increased temperature with high dynamic shear forces applied through the roller, whereas it decreased in autoclave processing as depicted in Fig. 12c and d. Comer et al. [158] derived through micro-CT that voids from unconsolidated carbon/PEEK prepreg are greatly stretched in the fibre direction as depicted in Fig. 12a and b. It was also discovered that there were more voids in the laser-assisted ATP whereby the mechanism here combines increased temperature with high dynamic shear forces applied through the roller, whereas it decreased in autoclave processing as depicted in Fig. 12c and d. This can be attributed to the inclusion of inter-laminar voids that are trapped during laying which are controlled through processing parameters and prepreg roughness. Furthermore, intra laminar voids reappear due to poor heat extraction may be the reason for the increase in void content [145]. To expound, intra laminar voids pivotally contribute to matrix softening, primary voids, and dissolved air. During in-situ consolidation manufacturing, the incoming tape and substrate are melted as well as bonded together through compaction that is cooled and crystallized. Prior to compaction, the matrix undergoes softening, thermal expansion, and rapid melting. Simultaneously, any dissolved volatiles and air left in the tape are released which facilitates gradual void formation within the tape [159]. Therefore, there is a possibility that even an incoming tape with a relatively low void content can begin exhibiting incremental void content in the automated manufacturing process due to the inadequately extracting of the heat to lower the temperature to below glass transition temperature (Tg) prior to releasing the consolidation pressure [158]. Thereafter, the compaction pressure is vital in preventing void growth and containing the intra-laminar and inter-laminar. Herein, it is understood that as the bonded material exits the compaction zone, the new interface temperature as well as that of the next layer below is substantially greater than Tg. This is a subject area that requires further investigation by optimizing the processing parameters and equipment components such as the roller geometry and this will aid in mitigating these mechanisms behind void formation [158, 159].

It was discovered that the sole method of reducing the inter and intra-layer void content is through consolidation or squeeze flow mechanism which is enabled by applying high consolidation force from a compaction device [160, 161]. The major questions to be answered and issues to be resolved remains:

- The relationship between the matrix shrinkage, void formation, curing kinetics, and gas diffusivity in prepreg processing.
- How the interface between plies and between the tapes for automated manufacturing impacts the void formation and modelling strategies.
- Where the total void content is beneath detectable limits, random or smaller voids can still be present and pose a danger from failure when subjected to in-service loads.
- The possibility of identifying the process factors which result to void formation with varying shape and size distribution.

Sebaey et al. [120] investigated the quality of thermoplastic composites that are fabricated through the ATP technique where the void content, fibre misalignment, and fibre distribution within the matrix were the parameters used to assess it. Through quantification from computer tomography and optical microscopy scans and comparison with the autoclave cycle manufacturing process, it was revealed that the ATP samples have a higher volume fraction of voids. Also, when the fabricated thermoplastic composite is compared to the thermoset (epoxy-based) composite, the thermoplastic composite indicated quality improvement in the form of fibre distribution within the matrix alongside the fibre misalignment (Fig. 13a).

For ATP, thermoplastic matrix crystallization occurs when fibre is subjected to tension, this accounts for the improvement of fibre misalignment in the ATP thermoplastic composite manufacturing technique. Although the autoclave cycle manufacturing process with 1 bar pressure and at a temperature greater than the melting temperature indicated improvements in fibre distribution and void contents in the matrix, this technique resulted in the decline of the fibre misalignment due to the polymer matrix melting during the process and enables under pressure curing at the same time each fibre is unconstrained (depicted in Fig. 13b). However, the autoclave cannot be used for certain matrices such as high-density polyethene (HDPE) as it does not resist heat at autoclavable conditions (at ~15 psi, and 121 °C) but can be sterilized. In terms of the TCP structure and functionality, the determination of the magnitude of the local deflection is considered a defect. The magnitude of the defect can influence the performance as depicted in Fig. 14a by Smit [53]. Tiny defects (size 1) on a microscale may not influence the performance of the pipe while a larger defect can reduce the residual strength. At a certain point (size 2) the residual strength is equivalent to the allowable strength which signifies the utmost defect size that TCP can resist without affecting the designed load.

As stated earlier that the essential parameters for TCP manufacturing are the consolidating pressure, melting temperature, and curing time during the melt fusion procedure. This can cause deviation from the theoretical design resulting in manufacturing-induced defects

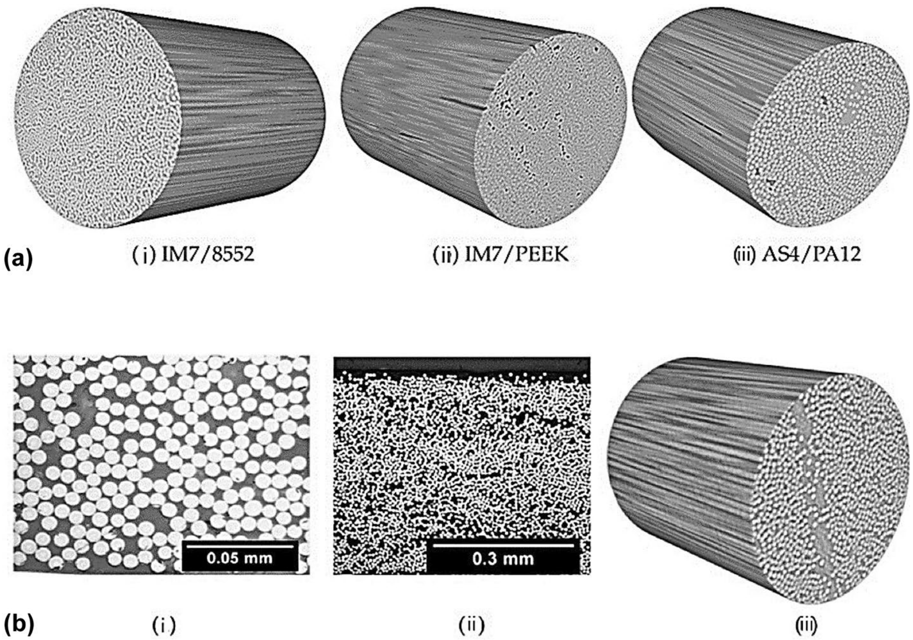


Fig. 13 **a** Constructed CT scans depicting fibre misalignments of tested samples obtained from ATP **b** Assessment of the thermoplastic composite (carbon fibre (AS4)/ polyamide 12 (PA12)) for **i** high magnification **ii** low magnification **iii** 3D CT scan [120]

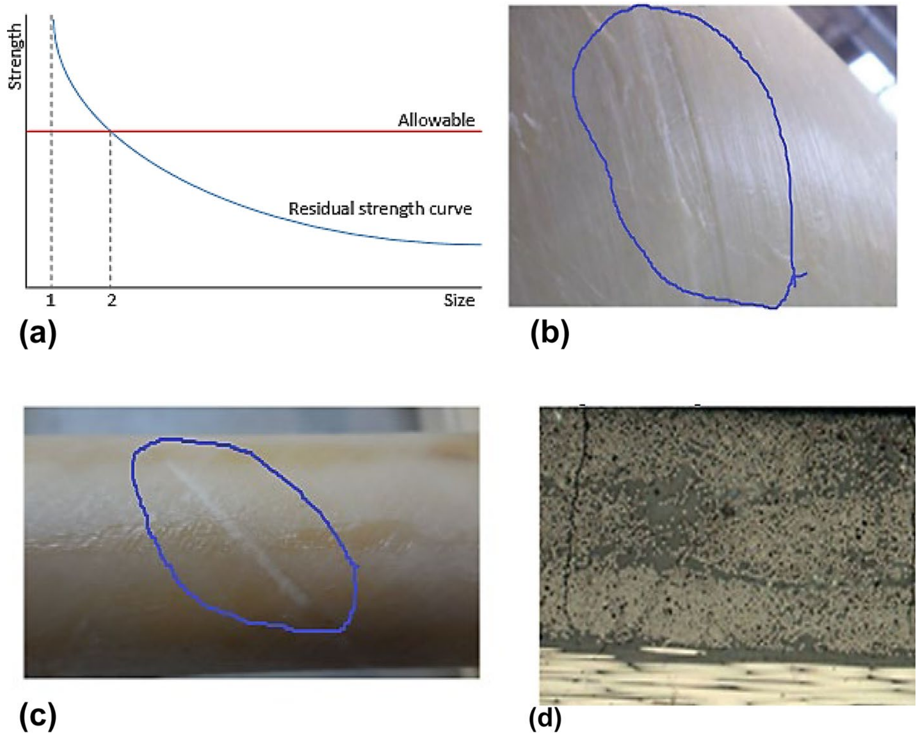


Fig. 14 **a** Residual strength to defect size relationship, Illustration of **b** gaps within a composite pipe, **c** void presence in the pipe [53] **d** the surface layer of carbon fibre reinforced polymer with transverse crack [162]

in TCP which are mainly voids and gaps. During the tape winding process, the tapes are required to be wound precisely to both sides. However, this is a complicated process as the melt fusion process can influence the geometry resulting in gaps. For gaps, the wound layer is absent leading to local low fibre which is depicted in Fig. 14b. The tape tension drags the next tape layer over the gap, this forms a bridge and mitigates out-of-plane disorderliness with the fibre. The gap is packed with surplus matrix material from the device and differences in thickness can be neglected. Gaps are defined by the width of the gap and the length along the pipe. Voids, in this case, are then formed due to air inclusions in the composite and most times the outcome of locally poor heating and consolidation. Irregularly shaped voids can possibly be due to nonuniformities in the substrate surface. Nonetheless, during manufacturing, voids are mostly because of gaps when there is a poor bonding of the underlying layer with and the gap layer during melt fusion and thus, has a shape that is associated with the orientation of the gap as depicted in Fig. 14c. This form of gap-induced void is different from other voids in terms of description and also as similar to gaps, void can be defined by the width of the void and the length along the pipe. Although for gaps, the interface between the plies is continuous, there is discontinuity for voids at the interface and this is a source for delamination. Void presence between the layers is a defect form that significantly affects the ILSS of composite structure [56].

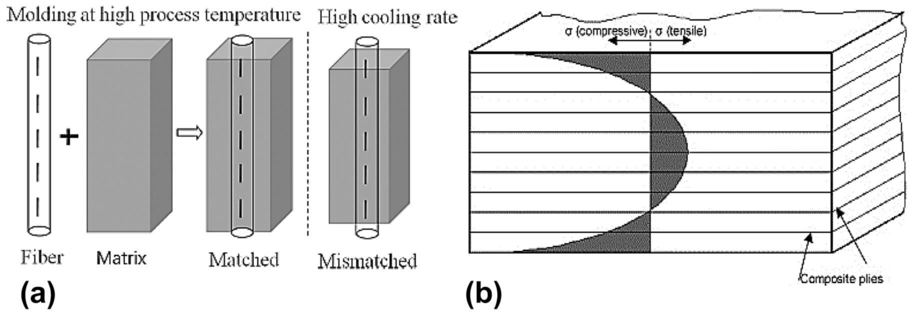


Fig. 15 Illustration of **a** mismatch occurrence from the matrix and fibre interactions in thermoplastic composites [156], **b** Parabolic residual stress distribution after cooling phase [166]

Residual Stress Another common matrix-based manufacturing-induced challenge is residual (thermal) stress formation. This stress does not cause secondary defects that can be categorized as manufacturing defects. However, the effect of residual stresses is specifically significant for the stability analysis of fibre-reinforced composite structures. Residual stresses are introduced during the cooling process and are evident in the cooled section. The tow steering along with the formed gap and overlaps contributes to the build-up of residual stresses. At this stage, tension from feed tow and the consolidation significantly influences the generation of residual stresses [163]. However, in certain applications, residual stress is artificially induced to facilitate stress redistribution. It has been accepted that the generation of residual stresses during composite part manufacturing for high-performing structures causes dimensional changes in end-cooled parts. Due to tolerance specification for the end part, the dimensional changes must be resolved either through modification of manufacturing process parameters which are currently done by process simulation (based on the ability to predict residual stress development and dimensional changes) or post-manufacturing using more costly approaches [164]. Herein, thermal-residual stress pertains to any form of stress formed from thermoplastic composite processing when the curing from elevated process temperature compared to ambient temperature (thermal history) for CTE mismatch between the matrix and fibre along with the anisotropic behaviour of the surrounding plies and the potential thermal gradient distribution in the ply of interest which essentially should be considered during the designing phase of the manufacturing process [162].

During the processing of fibre reinforced composites, stresses are developed at three varying scales. The main stress levels are within the separated fibres in a ply which are termed micro stresses (a constituent). In a unidirectional composite, there are two elements with vastly different properties for the polymer matrix and the fibre. Essentially across the material, the coefficient of thermal expansion (CTE) for fibre is substantially lower than the matrix polymer both at room and melt temperatures. Therefore, considering the condition of a single fibre surrounded by an infinite matrix, it was understood that the compressive stress across the axis is roughly three times higher than the stress in the radial axis. However, it should be noted that the effect of the fibre types can readily be reversed through stresses from the matrix. Another root cause of this level of residual stress is the phase changes during curing or crystallization [165]. Hence the mismatch in free strains in the matrix and fibre results in residual stress generation as depicted in Fig. 15a.

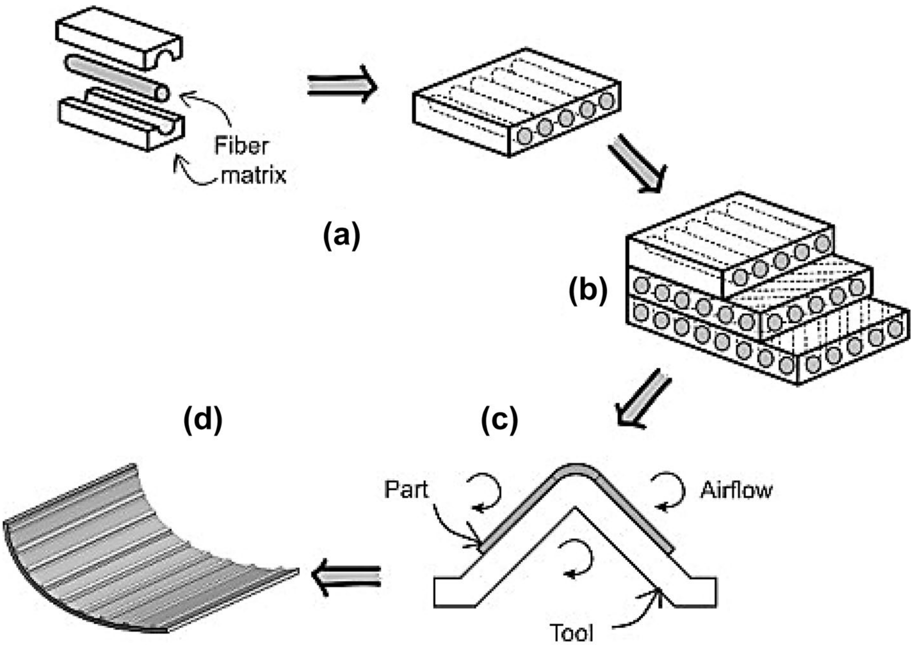


Fig. 16 Different size scale levels for laminated composites, **a** micro stresses, **b** meso stresses, **c** coupon level, and **d** global stresses [164]

However, deformations from fibre are substantially smaller than those created from the matrix based on the fibre CTE being smaller than the deformation from polymer matrix in the entire material and this has negligible influence on thermal residual stress within the composite created from fibre deformation can be ignored [162]. The second stress type to consider for continuous fibre reinforced composites are those generated at the level of ply to ply in multiaxial laminates because of the differences in CTE for the separate plies in varying directions which is termed macro stresses (lamination). Furthermore, at a larger scale, the third stress level is related to the different thermal histories of the laminate parts during the cooling phase. These stresses are generated through thickness which typically has parabolic distribution (Fig. 15b) and is termed global stress. Basically, the stress between the plies discontinues in combination with the degree of cooling and thermal history/temperature gradients contribute to residual stress development [165].

However, the influence of the lay-up sequence on the thermo-residual stress during manufacturing is a key challenge which includes the crystallinity of the matrix, angle ply, and fibre-fabric structures. The residual stresses rise with a differential increase between ambient temperature and stress-free temperature (SFT). SFT can be derived by heating the composite till there is no deformation. The thermal-residual stresses on thermoplastic composites because of the thermal history of the part [162]. Interested readers on residual stress types are referred to the excellent work by Barnes and Byerly [165] for further reading. With an increased investigation into residual stress development in composites, a recent stress level has been established to be coupon level (Fig. 16) with root causes being ply drop-off/termination, device interactions, and foreign inserts [164].

Additionally, the thickness and cooling/curing process have been identified as influential in the formation of residual stress in thermoplastic composites, and they vary across different materials. However, the degree of crystallinity can be similar at the start of the cooling stage. The use of the annealing approach in the curing phase can relax the residual stress as well as decrease the residual stress gradient which enhances the degree of crystallinity but may also increase processing time which subsequently will increase production costs [162]. The mould properties used in for the thermoplastic composite are also influential in thermo-residual stresses which is mainly due to mechanical and thermal interaction. The thermal interaction involves mostly the curing rate on the bottom and top surfaces of the composite while mechanical interaction concerns the creation of CTE mismatch between the composite part and the tool. This leads to compressive thermo-residual stresses on the surface plies close to the tool interface and through-thickness stress distribution emerges. On finishing the manufacturing process, based on the previously stated contributing factors, this stress is trapped inside the material and as a result, decreases

Table 5 Parameters that influence the formation of residual stress at several levels [164]

Levels	Stage	Parameter	
micro	Material	Fibre	Elastic and viscoelastic properties, Volume fraction, Architecture, Thermal properties (i.e., coefficients of thermal expansion (CTE))
		Matrix	Elastic and viscoelastic properties, Cross-linking/crystallization kinetics, Cross-linking/crystallization shrinkage, Thermal properties (e.g., CTE, conductivity), Volume fraction
		Interface (sizing)	Bonding properties
		Void	Volume fraction
	Process	Thermal cycle	Heating/cooling cycle
Coupons	Part	Geometry	
	Tool	Soft tooling	Thermal properties Thickness
		Hard tooling	Thermal properties Thickness Surface roughness Surface preparation (i.e., release agents)
	Process	Pressure cycle	
	Facility	Heat transfer coefficients (ambient)	
Global	Part	Inserts	
		Ply drop-off (terminations)	
		Geometrical features	sharp corners, cusp regions, holes, etc
	Tool	Substructure	
	Facility	Thermal history changes	lead and lag spots
	Post-process	Trimming and chamfering	
		Drilling	
		Cutting	
		Co-Bonding / Post-curing	
		Demoulding	

the load-bearing ability. Although the residual stress level can be considered negligible in comparison to fibre strength, it should still be considered for the design specifications at the matrix level. By understanding the influence of the different processing factors on the residual stress development there is a possibility of reducing the residual stress amount and hence improving the mechanical performance and design limitations of the matrix. Plausible parameters that can influence residual stress development at varying levels are listed in Table 5.

The possible defects that can be generated through residual stress have been identified based on the reduction of mechanical properties that occurs in the manufacturing process. The properties which are linked to the properties of the matrix and fibre as well as the interaction are considered here. For the effect of residual stress on the fibre, the thermoplastic matrix differs from thermosets as the bonding interaction between the thermoplastic matrix and fibre of the composites is identified to be van der Waals force (adhesion does not involve chemical reaction). Fibre waviness also occurs when fibre experiences axial loads from residual stress as the matrix cannot provide adequate support for a certain amount of transverse fibre and this deforms the fibre (micro buckle) hence waviness is generated [166]. The interface shear strength of the derived composites can substantially influence the thermo-residual stresses which cause debonding failure across the fibre axis and limits the end mechanical properties. Furthermore, for thermal residual stress effect on the interface of matrix and fibre properties, delamination or crack created where thermal residual stress is greater than the interfacial strength and the residual stresses present transcends into the matrix by means of micro-crack expansion as Fig. 14d depicts the basic transverse crack on the surface layer of a carbon fibre reinforced thermoplastic polymer that significantly impedes their mechanical properties.

With the increased investigation into residual stress development in composites, Zobeiry and Poursartip [164] identified stress levels at coupon level with root causes being ply drop off/termination, device interactions, and foreign inserts. Also, the thickness and cooling/curing process have been identified as influential in the formation of residual stress in thermoplastic composites, and they vary across different materials. However, the degree of crystallinity can be similar at the start of the cooling stage. The use of the annealing approach in the curing phase can relax the residual stress as well as decrease the residual stress gradient which enhances the degree of crystallinity but may also increase processing time which subsequently will increase production costs [162]. The mould properties used for the thermoplastic composite are also influential in thermo-residual stresses which is mainly due to mechanical and thermal interaction. The thermal interaction involves mostly the curing rate on the bottom and top surfaces of the composite while mechanical interaction concerns the creation of CTE mismatch between the composite part and the tool. This leads to compressive thermo-residual stresses on the surface plies close to the tool interface and through-thickness stress distribution emerges. During service applications, any initiated crack tip will initially increase the yield strength and create a transverse crack which causes the reduction of bearing capacity. The crack density will significantly rise with the composite going through thermal cycling, heat treatments, temperature, and ageing conditions, which clearly reduces the compressive performance of the composite.

In terms of inadequate curing, the melt fused manufacturing utilizes prepregs which include cutting prepreg plies, layup of plies on mould, drape plies to mould, high pressure and temperature, and demoulding after the mould curing at the appropriate temperature. To reduce cure time, fast curing matrix curing and high curing temperature are used. Reducing curing time through elevated cooling rate and demoulding temperature is an alternative for shortening the cycling time of the manufacturing process. However, this technique is mainly linked to the formation of internal residual stresses between the composite layers within the plies. Residual stresses are debilitating to geometrical dimensions and mechanical properties. It is obvious that residual stresses that occur during the manufacturing process are directly connected to the processing factors such as the time, cure rate, curing temperature, and mould temperature. Therefore, the curing phase through this process must be adequately designed and the influence of fast processing conditions on the composite properties must be understood prior to fast processing mostly for use in high-performance composite structures. However, there is a dearth of work done on resolving the generation of residual strains during the fast-curing process [167].

Furthermore, thermoplastic resins cover the collection of resins that do not go through a cross-link reaction when they are cured or heated. Since no cross-linking reaction occurs, this enables the thermoplastic resins to undergo melting which can harden indefinitely, and thus the thermoplastic curing process can be reversible as well as the material being recyclable. Previously, thermoplastics were perceived to be materials that are deficient in mechanical properties with key restrictions such as low glass transition temperature (Tg), poor solvent resistance, and low elastic modulus. However, an increased interest and research in high-performing thermoplastic materials has resulted in a variety of thermoplastics that can match or even exceed the chemical and mechanical properties of thermosets. This is derived through increasing the rigidity of the polymer through various techniques which include introducing reinforcements and rigid aromatic rings to increase the intermolecular forces and limit the backbone chain movement. Furthermore, thermoplastics display elastic–plastic characteristics thus the toughness is greater than thermoset which enables the material to sustain substantial damage without damage or crack formation. The major limitations of the thermoplastic matrix are the melt viscosity and high processing temperature. With high melt viscosity, there will be insufficient fibre impregnation. Processing and fabricating thermoplastic composites can be problematic because of the need for high processing temperature, poor bonding, and high viscosity. Several processing techniques have been examined for enhancing the impregnation and consolidation process and this can be achieved by reducing the impregnation length between the fibre and matrix [168].

3.1.3 Interfacial Bond Defects

Interfacial defects are mostly the result of poor bond generation at the interface either between the matrix and fibre or between the composite layers during manufacturing. It is plausible that unbonded regions of a fibre surface can occur when the fibre preforms which have been infused with resin do not wet the whole fibre surface. Trapped air between the layers can arise when the prepreg layers are stacked during manufacturing. These air pockets within the interlaminar area can be flattened during layer consolidation which causes no contact in the plane and hence no or poor bonding between the layers [169]. These defects are often termed delamination; however, this term is more suitably used to define debonding or bonded layer separation at the interfaces of the composite structure (Fig. 17a) [51].

Orthotropic composites (properties depending on the 3-dimensional directions) can be described as possessing several layers of randomly oriented fibres held together through a matrix where individual layers of fibre have a planar (2-dimensional) orientation [173]. Most times composite parts contain delamination. Possible causes of delamination are numerous and involve debris hits, manufacturing defects, foreign object strikes, and tool

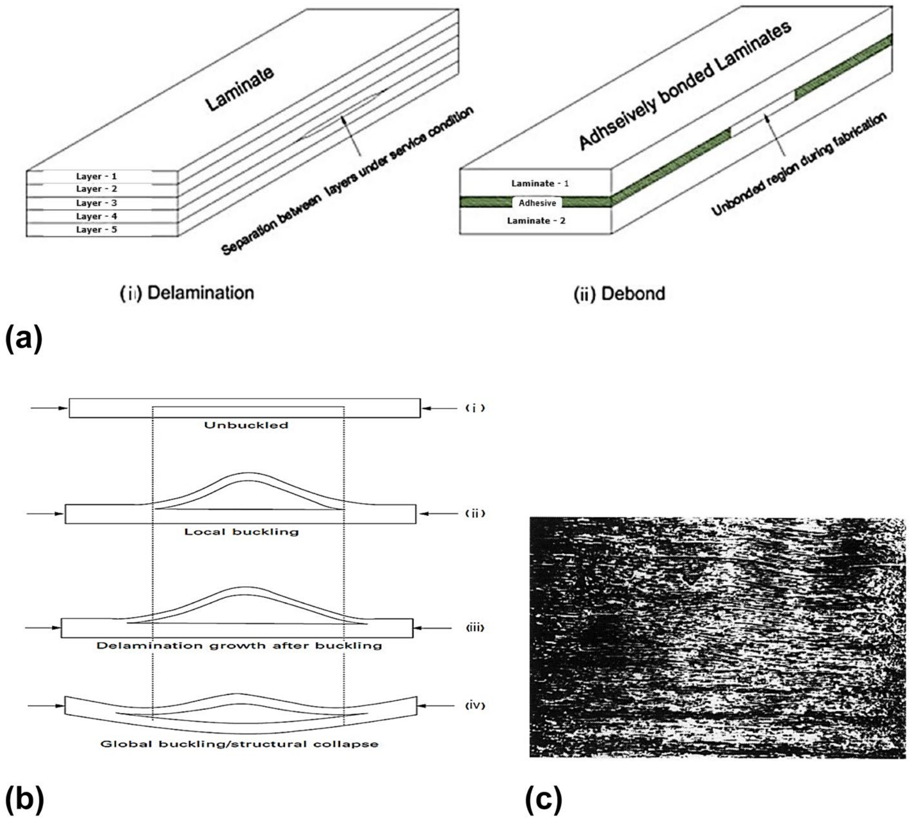


Fig. 17 Schematic representation of **a** delamination and debond [170] **b** The behaviour of delaminated composite planes subjected to compression (i) conditions for unbuckled structure, (ii) local buckling, (iii) delamination propagation post local buckling (iv) global buckling (structural collapse) [171] and **c** fibre waviness derived from filament wound pipe [172]

drops. Furthermore, at certain times and particularly the presence of spaces or near the edges in total initiates delamination due to the build-up of interlaminar stresses. The delamination type that is covered in basic discourse is present either internally or on edges [174]. The delamination can occur prior to loading the composite or it can also form after loading due to foreign body impact. This is an extremely vital challenge, particularly for laminated structures that are exposed to weakening loads (loads that can cause delamination growth and load that induces weakness in the structure, they both are influential in laminate failure). Delamination presence within a structure can cause local buckle which activates global buckling and hence induces a decrease in the general load-bearing capacity of the structure. This challenge, due to its importance, has amassed massive attention.

Observing Fig. 17b, the global or local buckling of the delaminated area may arise if a delaminated composite plate is subjected to in-plane compression. Figure 17b depicts the stages that generate delaminated failure when subjected to compression load. In certain cases, mixed-mode buckling can also occur where both global and local emerge concurrently in the composite. Hence, it is suggested that an analysis of the delaminated composite post-buckling should be carried out.

The manufacturing cycle for thermoplastic composites comprises three key phases. During the lay-up process, the matrix and fibre or prepregs are heated, consolidated, and hardened/solidified. During the heating phase, both the matrix and fibre are heated greater than the melting temperature (Tm) of the thermoplastic polymer matrix [168]. To ensure a final composite is of quality, the process needs consolidation and heating inclusion. Although there is no definite definition of the term consolidation. For the sake of clarification, consolidation will connote the series of mechanisms which are void reduction to enable the designed porosity levels to be attained, either maximizing the degree of crystallinity or minimizing internal stress, and the more relatable which is the adhesion between the plies during manufacturing which assist in understanding the interfacial consolidation between the bonded referred to as autohesion (adhesion). This autohesion phenomenon has proven to be a vital mechanism to be mitigated to render adequate final quality of the adhered part.

For facilitating adhesion, the composite substrates are squeezed together for some time at a temperature higher than the processing temperature of the matrix. As explained by Wool and O’Connor [175], the adhesion process comprises a series of 5 stages which are surface rearrangement, surface approach, surface wetting, diffusion, and randomization/layer combination. In the first two phases, there is no mechanical strength due to the presence of the original interface. Initially, for contact at a microscopic scale, any deformation of surface roughness should be propelled by wetting and contact pressure. This is termed intimate contact which when achieved the interface slowly dissipates through the healing process and the mechanical strength at the interface is then generated to facilitate an approach for the bulk property. When intimate contact is established, the macromolecules can roam across the interface by an inter-diffusion process also termed autohesion for two similar components and this is backed by the de Gennes reptation theory for a polymeric molecular chain. Overall, the manufacturing of high-performance composite structures is gearing towards the direction of rapid and continuous formats with the goal of shortening the cooling phase at a residence time of a few seconds [176]. The prevalent issues which may occur from manufacturing and the presence of high fibre volume fractions are:

- Low matrix amount present during interface melting.
- Internal stresses are inherent in all materials at different scales.
- Thermal history induces matrix modifications, particularly for high-performing composite parts which are processed at elevated temperatures and can create extra internal stresses that can possibly affect the adhesion strength.
- Restraining influence because of fibre presence, particularly for high fibre volume fractions with the average length between fibres being extremely small.
- Increased roughness because of the fibrous shape that causes variation in intimate contact from the matrix.

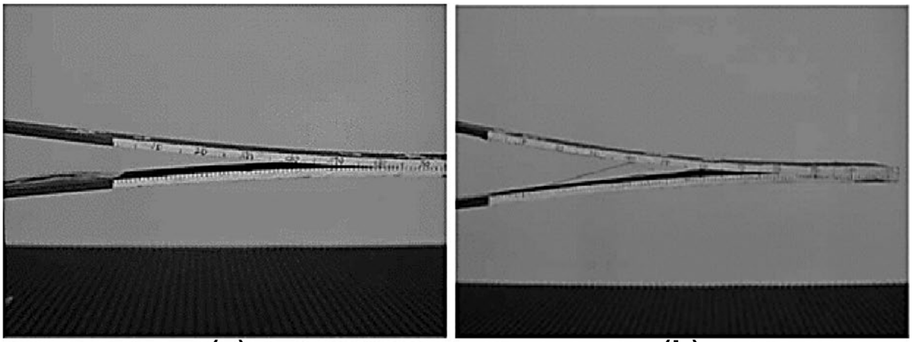
Delamination Defects Delamination is the most common failure type in composite materials. This failure phenomenon is a result of either imperfection while the manufacturing phase or the influence of external parameters through the service life of the composite such as the influence of foreign items. This failure also occurs through interlaminar stresses that are linked generally to the lowest through-thickness strength. This is attributed to the fibre laid in the laminate plane that does not reinforce the thickness, hence the composite depends on the closely weaker matrix to convey the loads in that direction [171]. A delamination is a form of layer deformation in fibre-reinforced composite materials, and it is based on the continuous pressure and stress on the material. This type of failure creates a flawed performance during the service life of the materials. The poor curing procedures create non-uniform pressure on the varying regions, which gives rise to regions of delamination.

The formation of delamination regions within the material can greatly decrease the strength of the composite during compressive loads and this is due to the buckling effect of the composite structure. Delamination can also be due to deterioration of the reinforcement through the thickness owing to interlaminar stresses from out-of-plane loading, ply drops, discontinuities from cracks, free edges, and tapered or curved geometry. Basically, when decohesion between the adjacent layer emerges, the delaminated surface grows which is similar to crack propagation in the direction that can be deduced. The mechanism for delamination failure mode can be initiated by the concentration of interlaminar stresses that arises in the presence of free spaces in the layer. Additionally, interlaminar defects can propagate when subjected to compressive loads. Although several works of literature have covered delamination at the in-service stage or equivalent, the effects of manufacturing on delamination growth have been relatively less covered by literature.

There are currently two prevalent categories of fibre to matrix defect types that are vital in the material design phase, and they are delamination in fibre reinforced composites and global fatigue cracks which include crack tips and crack propagation. Propagation of delamination is another prevalent phenomenon that arises in composites subjected to fatigue loads and can pose a grave concern in the structure specifically when subjected to compressive loads that result in local and/or global buckling [177]. Imran et al. [178] studied several forms of failure modes where interlamination delamination is among the major prevalent models. For delamination in thin-walled fibre reinforced polymer composite, structural stability poses a serious challenge as well as buckling in the composite structure affects the structural and mechanical properties. Hence, this mode of failure should be regarded during the design process prior to initiating the fabrication process. Delamination may also occur from service loads at stress concentrations such as ply drop-off and spaces.

Based on the compression process, the delaminated composite plane is inadequately capable to withstand compressive loads. Based on Hwang and Mao [179], the decrease in the ability to resist compressive loads is due to the delamination properties in the composite which include shape, position, and area of delamination. Nonetheless, if the delamination is not formed in the composite within a short time, then the buckling of the delaminated composite may not signify the sudden failure. It is also now established that delamination always propagates after buckling. Hence, regardless of buckling, the delaminated composite platform is still susceptible to elevated loads till delamination forms. The main propagation possibility of the delaminated composite plane indicates the ability to resist compressive loads. Therefore, understanding the influence of delamination on the buckling and after buckling is vital to suitably design the composites and reliably use the finished component [179].

For certain structural details which include adhesion (bonding) and joints, tensile loading conditions can create a local compressive stress circumstance that is essential for delamination growth close to the joined spots. In addition, delamination is initiated in the bearing plane when the bond fails to occur because of the bearing failure mode. These delamination failure modes have a tendency to occur when the material is subjected to tensile or tensile-compression fatigue loading conditions. Zhang and Fox [180] studied the influence of the manufacturing process on delamination fracture behaviour for a carbon fibre reinforced polymer. The two manufacturing processes used are typical autoclave



(a) (b)

Fig. 18 Delaminated DCB samples subjected to mode 1 loading **a** autoclaved sample, **b** quickstep process [180]

curing and quickstep processes which are out of autoclave production with a faster cure cycle than the auto process. Artificial delamination was introduced in all samples where double cantilevered beam (DCB) testing of mode 1 loading propagated the delamination as depicted in Fig. 18a and b.

Furthermore, it is deduced that propagation in the quickstep was slightly higher than that of the autoclave sample. Also, the three fracture types that occurred for both processes are interlayer fracture, interface fracture, and intralaminar fracture. These fracture types influence the direction of the delamination to the resistance curve during crack growth. When the applied load (cyclic or static) on a composite structure, the damage initiation, and growth arise in sequences of events through which each mode builds up and interacts with another. Based on the heterogeneous and anisotropic behaviour of the composite materials, the damage potential is significant. However, for fibre reinforced composites, there are three major failure modes which are intra-ply cracking, interlaminar matrix delamination, and fibre failure which are influential in their mechanical properties. Other forms of damage may basically change the load severity at which these three failure modes may arise. Amongst the three major failure modes earlier described, the interlaminar matrix delamination is the most prevalent [173].

The delamination of a structure under in-plane loads is a nearly vital failure mode that can cause local stress concentration in load resistance plies, stiffness loss, or local instability which results in load path redistribution that may lead to structural failure. Hence, delamination is the most popular service life defect hampering failure propagation mode. Delamination propagates at the interlayer face in multidirectional long fibre composites. As previously stated, delamination has a severe impact on the compressive properties of composites. This type of interlaminar fracture decreases the load-bearing fibre stability which leads to a localized buckling failure mode at small loads. Manufacturers tend to address this issue by improving the toughness features of the matrix materials. Modern means of achieving this on a thermoplastic composite is by using a tougher matrix to attain a sufficient resistance to delamination and hence enhance the post-impact compressive features. Delamination of TCP structure will result in the buckling (local) of the delaminating layer which is prior to global buckling, there is also the possibility for mixed-mode buckling when the corresponding out-of-plane displacement in the substrate and delamination layers are in the opposing direction. Delamination is a common occurrence in composite structures and hence it is very significant that delamination does not hinder the performance of a structure during operation. Delamination propagation occurs when ILSS surpasses the matrix strength between the plies [181]. However, delamination may be beneficial based on the load-bearing ability of the composite structure. An instance of this was proven by [136] from a fracture test on multidirectional carbon fibre reinforced polymer materials. The result showed that the appearance of delamination zones throughout the stress raiser like a sharp notch act as stress field redistribution and defect isolation. Other suggested techniques for delaying and preventing are 3-D weaving (thickness created from stacked layers), adhesive interleaving, matrix property improvements or tougher resin development, through-thickness stitching, braiding, and novel design considerations to lower interlaminar stresses [173, 182].

Interlaminar Stress Defects In brief, the delamination may be caused by interlaminar stresses resulting from impacts, irregularities in structural load paths, or structural discontinuities. Certain design factors which can induce the local out-of-plane loads that lead to interlaminar stresses have been identified as straight or curved free edge, spaces, ply drop, or terminations for tapering/thinning the thickness, bonded or co-cured joints, bolted joints and cracked lap shear samples. For all these conditions, regardless of if the remote load is in-plane, the local loads close to the structural discontinuities can be out-of-plane [173]. Excluding the mechanical loads, the temperature and moisture content can also create interlaminar stress on the part. These may be generated through (a) moisture gradient through-thickness of layer (b) residual thermal stresses from curing of the part from higher curing temperature or because of differences between the stress-free and temperatures and, (c) residual stresses caused by moisture absorption in the final part.

The generation of interlaminar stresses close to the free edges of the composites is a vital phenomenon. These stresses are generated as a result of the mismatch in properties such as poisons ratio and the ratio of extensional strain to shear strain (coefficient of mutual influence) between layers. Where there is no mismatch of these between layers, interlaminar stresses do not occur regardless of mismatch in shear and elastic moduli [173]. However, the above statement does not mean that delamination between layers with the same orientation will not arise. The delamination between these layers may arise when there is an interface moment that is created through the surrounding plies of varying orientations or elastic properties. The mismatch in Poisson's ratio generates shear stresses and interlaminar normal while the mismatch in coefficient of mutual influence between layers causes ILSS close to the free edge of the part. The magnitude of these stresses relies on the magnitude of the differences in the mismatched properties, shear, and elastic moduli as well as stacking series, loading mode, and environmental situations.

Considering these factors, TCP is subjected to environmental exposure such as marine conditions, and their long-term safety, working efficiency, and resistance to this exposure have received attention [161]. The perspective to address is by studying the coupling effect of moisture diffusion and thermal stresses which are combined to be termed hygrothermal. Hygrothermal degradation in fibre-reinforced polymer composites can be classified into the decrease of glass transition temperature (Tg) and developed stresses from hygrothermal expansion. In detail, moisture absorption lowers a polymer matrix Tg due to plasticization created from the breakage of the van der Waals bonds between the molecular chain of the polymer [183]. It is understood that moisture degrades the mechanical properties of fibre-reinforced polymer composites mostly occurring at the fibre-matrix interface. Moisture absorption is damaging to composite as it impairs the matrix to fibre bond where unfortunately the TCP is utilized mostly submerged in water from the offshore conditions [161]. In addition, the variations in the stacking sequence of the plies induce strain from hygrothermal expansion between facing plies and this induced strain/strain can be combined with external loading. These circumstances result in the reduction of the strength and stiffness which is largely influenced by the matrix in fibre-reinforced polymer composites [183]. Conventionally, the effects of temperature and moisture are simultaneously investigated to identify the combined effects of the two conditions.

The coupling effect (hygrothermal strain) of the hygrothermal expansion was observed by Meng et al. [183] to alter the ILSS distribution so that the stress is asymmetric around the mid-plane. In addition, the maximum interlaminar shear stress value exhibited a 15% decrease after water absorption in comparison to the dry set-up. Vina et al. [184] deduced that the behaviour of interlaminar shear strength is similar to the tensile strength and also verified that moisture can alter the microstructure and properties of certain reinforced materials. The interlaminar shear strength declined when exposed to moisture, especially within the first 5 days after which the material retained its property. Although the change in temperature had no mechanical effect on the interlaminar stresses, it serves as an initiator for water molecules to diffuse through the material, hence, the material will absorb more moisture rapidly till saturation point. Ryan [185] concluded that both the interlaminar shear strength and modulus exhibited a maximum reduction of roughly 20% and 10% respectively with rising equilibrium moisture content while for the transverse modulus, the exposure to moisture conditioning had no effect. Through the short beam tests, Majerski et al. [186] realized that the ILSS value decreases when exposed to environmental conditions. Fibre-reinforced composite exhibited a decrease in the range of 12–27% for the interlaminar stress. Consistently, the test configurations with higher thickness are typified as lower strength. During bending from the test, the shear stress proportion is relatively large which is the rationale concept for the failure concentration site being mostly in the interlaminar region. Moisture can influence both polymer matrices by weakening them as well as altering the bonding quality of the ply interface.

Interlaminar stresses play a vital role in fracture initiations during bending and in terms of the failure mode, composites without water ingress have the matrix provide sufficient adhesion to the reinforcing fibre while the failure mechanism involves the debonding of the matrix–fibre interface. Post moisture absorption, the reinforced fibre has a bare surface in certain regions which infers that there is a deterioration of the adhesion at the fibre-matrix interface and their possible debonding. Noteworthy, the matrix fractures with exhibiting a more ductile behaviour. This deduction establishes the rationale for moisture ingress causing polymer plasticization and the weakening of the fibre-matrix interface. Similarly, Majerski et al. [186] presented that the fracture morphology of fibre reinforced composites postconditioning at environmental factors is significantly more complicated. The property deterioration at fibre–matrix interface causes the initiation of cracks delaminating fibres from the matrix and a change in the direction of crack propagation. When the crack delaminates the fibre at great length, this fibre is fractured. Subsequently, this microcrack deviates the propagation direction till it gets to another fibre. This affirms that the degradation of the matrix and the matrix-fibre interface is the salient aspect that ascertains the property decrease due to the influence of environmental constraints. For hygrothermal conditions, Yu et al. [161] deciphered that the addition of silane was able to establish chemical bonds that enhance the mode I and II fracture toughness but no changes in ILSS as the stress does not influence the matrix properties while the introduction of carbon nanotubes enabled the absorption of energy due to their greatly flexible elastic feature during deformation.

Another parameter that influences the interlaminar stresses is ply thickness. Thicker plies are inclined to enable elevated interlaminar stresses, hence causing speedy delamination. Although the discussions have mainly covered mechanical loads, the effects of residual stresses from moisture content and temperature changes must be accounted for. Residual thermal stress is always present in the part because it is curing at a higher temperature and can significantly influence the interlaminar stresses. Impact loads can cause several delaminations which can grow in combination with local buckling which massively lowers the residual compressive stress. The occurrence of delamination is connected to manufacturing defects or due to in-service impact damage. It should be known that barely any damage is obvious at the spot of impact on the surface, but internally the part has undergone significant damage [187]. When a laminate is struck by an impactor, for instance, the area of the material that has been impacted is compressed and transfers laterally in a shorter time than needed for the general response of the structure (Fig. 19a).

The large, localized deformation gradient leads to huge transverse shear and normal stresses which can make the damages grow and subsequently fail. Another influence of the impact is the formation of compression stress waves which transfer from the impacted surface through the thickness. This wave is reflected from behind the surface as a tension wave which may lead to failure at the initial weak interface resulting in slight fragmenting of parts of the end ply. Both local out-of-plane deformations and internal stress waves may commence delamination at the interface where there is a significant change in the ply angles. The dimension and amount of the damage in the part rely on the geometry, size, and shape of the structure, the impact energy, and the loads on the structure during impact. At lower impact velocities, the part can react by bending and fail either through flexural failure or shear causing delamination relying on the beam length. A relatively higher velocity has a different mode which can be caused through the combination of out-of-plane deformations and stress waves as detailed earlier. This damage can lead to delamination, matrix cracking, and fibre failure. Where the velocity of the impact is relatively high, the part behaves rigidly causing a shear out and full penetration of the impact.

Matrix Cracking Defects Another source of delamination formation in a fibre reinforced composite is the matrix cracking in off-axis plies. Defects are complex as their formation can be influenced by several parameters which include the material (chemical compatibility, loading, fibre orientation, size, matrix, and fibre), the type of manufacturing process, and their application (thermal mismatch, mechanical stress, etc.). Immediately micro-cracks are formed, and the next step will be the propagation of cracks till material failure. For fibre reinforced polymer composites which include unidirectional and multidirectional fibres, will generate varying crack formation as well as propagation behaviour. Crack growth and formation can be influenced by various chemical reactions between the fibre and matrix, this also influences the bond strength between them. Regardless of defect formation at the commencement of the fibre and matrix interaction and the manufacturing process goes perfectly according to design; defects can still be induced from residual stress arising from the thermal mismatch between the fibre and matrix or through material disintegration from mechanical load gradually.

In an instance of fibre-dominated defect, microcracks form when the fibre edge is detached from the matrix on slight loading. This is commonly occurring in discontinuous-fibre reinforced polymer composites where the fibre edge turns to a stress concentration location. Similar conditions can also occur for continuous fibre edges will have various possible effects. One possible outcome is that cracks grow across the fibre interface to the matrix and the composite fails. Another possibility is the crack growth in a normal

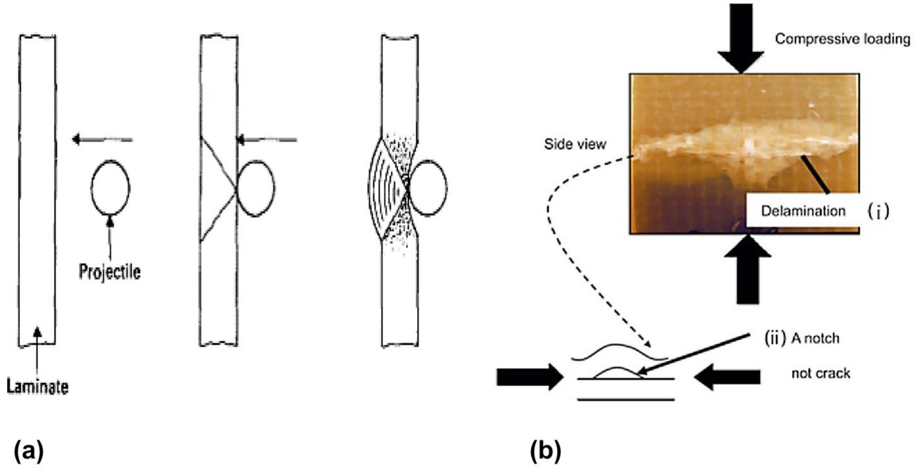


Fig. 19 **a** Deformation of laminate from impact [187] **b** (i) In-plane/internal delamination induced from impact in a fibre reinforced polymer composite grows when subjected to compressive load from compression post-impact test [188]; (ii) the delamination growth area across the interface is a notch rather than a theoretical sharp crack [189]

direction to the fibre across other fibre causing a rapid composite fracture. If both conditions are subdued, an elevated load leads to more detachment between the matrix and fibre edge which creates more microcracks at other locations. Each formed crack is transformed into a stress concentration location and impacts the crack propagation mode till it generally fails.

The investigation by Ponomareva et al. [190] concluded that points from particulates or sharp edges used as reinforcement are transformed to stress concentrators which enables microcrack formation within the composite. At certain times the atmospheric condition affects the application of the composite as it can serve as a source of cracks whereby an example is a phenomenon termed environmental stress cracking (ESC). Here, the polymer composite might be submerged in a liquid under stress. Gradually, material degradation occurs and subsequently microcrack formation starts on the material. The liquids then penetrate through the cracks and further decrease the strength of the region. The microcracks then rapidly grow with the degradation which finally causes material failure, and this occurs at a reduced stress load when compared to a standard environment.

In conditions where the fibre in the composite consists of layers encapsulated by the matrix, the interface between the matrix and fibre will be the weakest site. The structural performance of the composite will rely greatly on the interlaminar characteristics. Therefore, delamination which can be categorized as a subset of crack propagation in composites can arise when peel stress (tensile stresses arising in the bonded region due to peel or tensile loading of interlayers as well as in shear loaded joints from bending moments that arise from heterogeneous loading) surpasses the tensile strength of the matrix [191]. Figure 19b depicts impact-induced delamination in a fibre-reinforced polymer composite.

As previously stated, the faults or damages can weaken the mechanical properties of the composite structures thus influencing the structural performance. The challenge faced during material design is the consideration of barely visible damage on the surface which is the root source of the worsening of the structural performance. The current application of composites is restricted to supplementing structural parts which are designed to perform at optimum strains adequately reduced that no degradation of the structural performance occurs from impact damage. However, heavily loaded high-performing structures are designed to adequately bear loads at elevated strains which makes the structural performance susceptible to impact damage [192]. Where the end part is designed to retain low strains, the structure is expected to be dense which defeats the purpose of using composites. Therefore, to increase the damage tolerance or decrease delamination growth, several methods can be considered and some of them are briefly explained below.

Improvement of matrix – delamination propagation in a composite relies on the interlaminar fracture toughness which then depends on the matrix material toughness. With elevated resin, toughness comes a significant increase in composite performance from four key approaches which are the toughening of the matrix (matrix may be brittle and will require toughening through adding copolymers, novel curing agents, or secondary phase which includes reactions with rubber), light cross-link of thermoplastics, use of crystalline thermoplastics, and linear/flexible thermoplastics (appealing due to the combining factors of solvent resistance, high fracture toughness, and high flexural modulus). Furthermore, through-thickness reinforcement has been proven that 3-D integrated structures created through-thickness stitching or 3-D braiding process provide enhanced fracture toughness, damage tolerance, and are capable of resisting out-of-plan tension loads when delamination is stifled through this method [173, 193–195]. However, through stitching, the tensile and compressive strength of the composite when compared to unstitched composite for pristine specimens improved by roughly 25% [173]. Another approach is interleafing which entails the sandwiching of thin films of high shear strain and high toughness between the layers to be an effective means of improving the damage tolerance of composites. This offers beneficial improvement e.g., in compressive residual strength post-impact compared to pristine composite parts. However, this method is useful only when the failure happens by delamination and ineffective when transverse shear is the failure mode hence improving the shear modulus of the matrix is vital.

Certain design consideration guidelines can be considered for minimizing interface normal stress occurrence are attempting to reduce the geometric discontinuities and free edges which may always be challenging. A suggestion of reinforcing the free edges as an efficient way to avoid and/or delay induction of delamination. Other design configuration details to consider for curbing the damage propagation to enhance the damage tolerance of the part are first, a discrete-stiffness design through the regions of low axial stiffness which has more impact tolerance, and secondly, mechanical fastening of the parts together tends to effective of mitigating damage propagation which consequently improves damage tolerance. For more details on mitigating and predicting delamination, the reader should further study the work done by [173].

3.2 Examples of the Impact of the Defects on Composite Mechanical Performance

3.2.1 Strength and Stiffness

Aziz and Ansell [196] determined the mechanical properties of fibre reinforced polymer based on the effect of fibre alignment and treatment (alkalization). It was observed that generally, the mechanical properties such as the flexural modulus and flexural strength were high at a low fracture. This indicated that there will be a trade-off between the maximum strength and toughness as they cannot be achieved simultaneously, and the composite structure should be designed to fit the application and intended mechanical properties. Also, through the thermogram from the conducted DSC, the moisture content within the composites tends to generate plasticity within the material which subsequently reduces the mechanical properties. Through dynamic mechanical analysis (DMA) the treated fibre composites have higher dynamic modulus and lower measured energy dissipation which signifies improved interfacial bond strength and adhesion between the fibre and matrix resin with weaker impact properties. This alluded to an improvement within the range of 20–139% for impact, flexural and tensile properties of aligned long fibre thermoplastic composites in comparison with randomly oriented long fibre thermoplastic composites [197]. Also, Katsiropoulos et al. [198] reported that an improved fibre alignment for conventional (multi axial) carbon fibre types can improve the tensile strength of the final part compared to the use of commingled solutions. Furthermore, where waves from fibre misalignment were noticed and this enabled the formation of local buckling, and where fibre alignment is satisfactory, the compressive strength increases and the compressive properties collectively. Also using carbon fibre as the reinforcing agent in the composite material, commingled carbon fibre significantly reduced the tensile properties while the conventional fibre form had better fibre alignment and tensile properties too.

Yeung and Rao [199] explored the mechanical properties of pultrusion manufactured Kevlar-49 thermoplastic-based composites through sets of experiments and subsequently compared them to theoretical predictions. From the pultrusion process, fibres did not align in the uniaxial direction. This fibre misalignment serves a crucial role in influencing the exact compressive strength. Furthermore, the fibre limited the elasticity of the final part which contributes to the increase of composite strength. Through fibre misalignment, buckling is initiated as the matrix begins to yield. Post yielding, the matrix surrounding the fibres becomes hardened. This failure process continues, and the mechanism causes an oscillating behaviour of the load–displacement curve. Through the experiment, there was a 10% decrease in compressive strength with respect to the theoretical model and this was attributed to the expected slight deficiencies during the manufacturing process. Fibre misalignment and waviness were also identified as a source of composite strength reduction. It was also confirmed that fibre waviness/misalignments and matrix nonlinearity operate sequentially to generate micro-buckling loads that are less than the elastic results for straight fibres.

Alwekar et al. [197] also worked with long fibre thermoplastic composites but processed them through extrusion compression techniques. It was determined that the strength of the composite is linked to the critical fibre length while the stiffness typically relies on the fibre alignment and fibre content/volume present in the composite. Through this extrusion compression moulding, random orientation is generated (based on the location and geometry) and the composites fabricated from melt extrusion created a structure with aligned fibre. Although the efficient fibre length distribution is reduced, the long fibre thermoplastic composites can attain excellent mechanical performance if the fibres are highly aligned. Hence, through understanding the link between the process, microstructure, property, and mechanisms, the influence of anisotropy, enhanced quality, and functionality for in-service applications can be achieved. Bar et al. [200] observed that a high viscous thermoplastic matrix contributes to the induction of fibre misalignment into the composite structure. This factor inhibits the mechanical performance of the fibre-reinforced composite. Through surface modification of the fibre, the use of prepregs during thermoplastic composite manufacturing can resolve the shortcomings. Unlike natural fibre, synthetic fibre possesses a longer fibre length. Hence, it may be challenging to prevent fibre misalignment in the composite structure. From the work done by Van Hattum et al. [201] on the experimental study of powder-coated long fibre reinforced thermoplastic composites in the form of prepregs. The tensile properties of unidirectional fibre composites were obtained as a function of fibre length and fibre volume fraction. The effect of the fibre length and volume fraction on the composite confirmed that through impact and tensile tests, the modulus of the prepregs increase with fibre content and this was attributed to the increasing level of anisotropy. While through flexural test for fibre length at constant fibre volume fraction, it was observed that the strength and flexural modulus reduces slightly with increasing fibre length, and this indicates a negligible effect. There was also an observation that for all the studied samples, the prevalent fibre orientation is the perpendicular direction hence the increment of mechanical properties with an increase in volume fraction. The key cause of the different orientations is the effect of fibre orientation within the sample, it is mostly observed at high volume fractions from process-induced fibre misalignment. The effect of the manufacturing technique on the mesostructured was established by Piggott [172] where most fibre reinforced composites comprise typically stacked straight fibres. In terms of the orientation using prepregs, the aligned fibre form provides prepregs with the smallest fibre deviations. However, the mould material is influential here as it can determine the fibre straightness. It was observed that wavy fibres were produced where woven fibre prepregs are employed as depicted in Fig. 18c.

Pultrusion is also known to create wavy fibres, however, it is highly plausible that carefully inserting fibre into the mould would lead to much more aligned fibre where waviness is a challenge. The same observation was made by Souza et al. [202] processed and characterized a commingled long fibre jute reinforced polypropylene (jute/PP) composite. Through the compression moulding process, fibre misalignment is induced and can be connected to the degree of fibre interweaving where during processing seems to bend or deform regularly. To optimize fibre alignments, it was recommended that processing conditions should be improved. However, that is for ideal conditions but practically the fibres are generally misaligned in thermoplastics in comparison to that of thermosets which can be extremely minute. This misalignment/waviness decreases the tensile properties to a certain degree but significantly influences the compressive properties while benefiting the shear properties of the composite structures. The waviness can be mitigated through appropriate material selection for raw materials (preferably prepregs) and processing parameters such as the mould used. Hence, there is a direct link between material properties and the manufacturing process. It was suggested that in terms of fibre contents, it is essential to consider the anisotropic material properties for a proper design of the final component.

Zhang et al. [203] studied the mechanisms for void reduction through an oven vacuum bag process for fabricating high-performing carbon fibre thermoplastic composites. The common void reduction mechanisms through the oven vacuum bag process are through-thickness air diffusion (debulking) and in-plane flow to the edges of the part through permeable interlayer areas produced from the prepreg surface roughness. The void reduction in the structure with a closed perimeter is influenced by air diffusion through the thickness of the entire structure which reveals a very significant degree of void content post oven vacuum bag process. For the parts with unsealed edges for the vacuum, air diffusion from the single-layer moves through the permeable interlayer which basically results in void-free parts. It was discovered that the edge condition and inter-layer permeability are essential in void reduction and reveals that low void content can be attained in thick section thermoplastic composite structure through this cost-effective manufacturing process. The entrapped air is present in prepreg tapes and between layers during lay-ups and should be extracted during the process to achieve a high-quality material ($< 1\%$ void content). However, future work was recommended to investigate the relationship between the interlayer permeability and surface roughness, and the advancement of interlayer permeability during processing is advised to create further directions for processing high-performance thermoplastic composites.

3.2.2 Interface Shear Strength

Chen et al. [204] experimentally investigated the mechanical performance of laser-assisted AFP composites based on the crystallinity and the void content. There was an inconsistent trend as depicted in Fig. 20a and d for the crystallinity and strength of the tested composite which signifies the void content at varying temperatures in the part is significantly influential to the mechanical performance over the crystallinity effect for the AFP manufactured composites.

It also alludes that the highest crystallinity and strength of the composites were attained at varying tool temperatures, and this signifies that the void contents influenced the mechanical properties of the composites. Post autoclave treatment, the compression strength and ILSS of the composites were elevated based on the reduction of void contents reduction which consequently improves the crystallinity as depicted in Fig. 20c and d of the reduced void content. The autoclave treatment was also able to eliminate the thermal history (changes in sample temperature as a function of time during a test/process) of the AFP composites. This is confirmed through the constant crystallinity value as a function of lay-up/placement speed. Hence, the ILSS of the composite post autoclave treatment was almost free of the placement rate at no less than a certain speed (6 m/min) according to Chen et al. [204].

Kumar et al. [205] studied the impact of the curing cycle on the mechanical and thermal behaviour of polymers. No significant change in ILSS was noticed at elevated temperature (80 °C) over the whole curing time. When it got to 110 °C a straight increment in ILSS was noticed with time (even for about 12 h). For samples post-cured at 140 °C a quick enhancement in ILSS occurs gradually and is subsequently followed by saturation. Where all possible combinations of curing temperature and time are considered, optimum values for cure temperature and time that indicated significant improvement in thermal and mechanical properties are noticed at 140 °C for 6 h. This implies that under these conditions the monomers are optimally activated for further adhesion. The cooling cycle is a strong function of curing time and temperature is directly linked to the glass transition temperature (Tg) of the matrix. This transition temperature covers the transformation of the polymer from glassy to a rubbery state, thus determining the applicability of such material at a certain temperature with an extent of reliability and safety.

Furthermore, it is expected that the interface shear strength derived in the composites is significantly influenced by the thermal-residual stresses that consequently cause debonding damage across the fibre axis and hampers the end mechanical properties. Thermo-residual stresses generated during the processing phase have a substantial influence on thermoplastic composites which are created through layer anisotropy, cooling rate, the interaction between matrix and cooling rate, and CTE mismatch. The newly created thermo-residual stresses limit the damage resistance, dimensional ability, and mechanical properties of the thermoplastic composites. The effect of residual stress on thermoplastic composite's performance has been widely investigated based on which properties are dominant in either matrix or fibre materials. The influence of the interaction between the polymer matrix and fibre on the thermoplastic matrix differs with

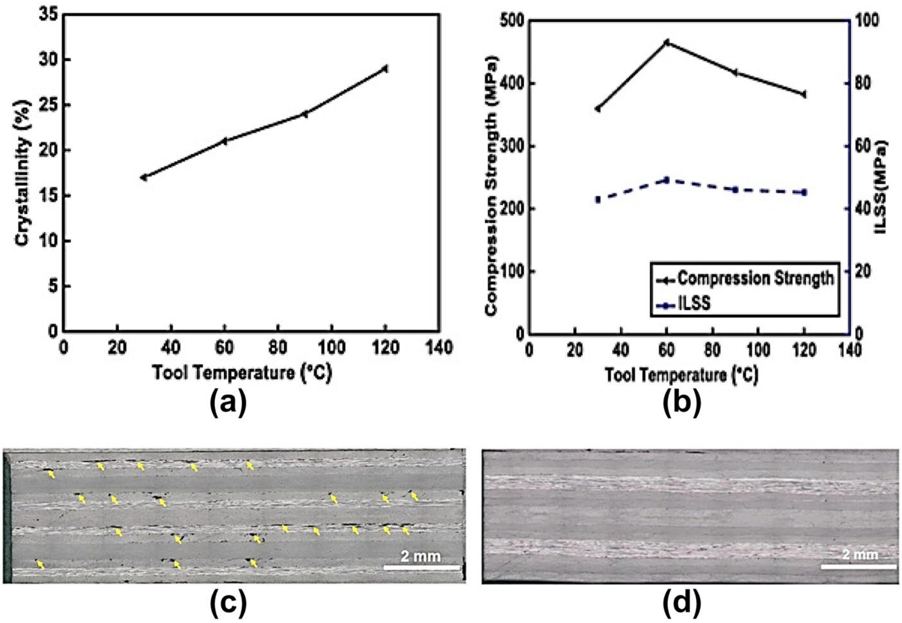


Fig. 20 AFP composites that are subjected to **a** Crystallinity and **b** interlaminar shear strength and compression strength, as a function of tool temperature. Cross-sectional view of AFP manufactured composite though microscopy of **c** pre autoclave treatment and **d** post autoclave treatment (yellow areas signify visible voids) [204]

thermoset with the bonding interaction between the matrix and fibre of the thermoplastic composites being Van der Waals force (weaker bonding that does that involve chemical reaction).

The study by Zhang and Fox [180] noted the occurrence of fibre breakage in the quickstep samples during the delamination process which heavily influences the fracture toughness for propagation. The quickstep cured samples also displayed a stronger matrix to fibre adhesion than the autoclave technique when the indentation-debond test was carried out. Also, through-thickness failure owing to interlaminar stresses is considered first, and the effect of delamination in impact and compression after impact. There is a way in which in-plane failure can occur by delamination and matrix cracks combining to produce a fracture surface without the need to break fibres [206]. Noteworthy, the effect of these defects on the performance of composites has not been thoroughly understood. This challenge stems from determining the effect on the properties in reproducing the defects in test samples that can then be tested and the application of appropriate monitoring techniques during testing.

3.2.3 Fracture Toughness

Saenz-Castillo et al. [207] studied the void contents and mechanical properties of composites fabricated through hot-press, vacuum bagging, and automated techniques. It was discovered that at similar void contents, the in-plane shear modulus of the composites through AFP was less when compared to hot pressing and vacuum bagging techniques. For the vacuum bag samples, the trend of the in-plane shear modulus indicated a substantial reduction (22%) when the void content value is above 10% while for the hot pressing, there is also a substantial reduction of shear modulus (33%) from beyond roughly 9% void content value. In terms of the in-situ consolidation, a significantly lower shear modulus value was attained in comparison to the other procedures. Chen et al. [204] and Saenz-Castillo et al. [207] attributed the low in-plane shear modulus from AFP composite manufacturing method to crystal morphology generated during ultra-fast cooling of the part. However, inconsistencies such as void concentrations as well as irregular fibre distribution within the matrix can be considered to generate a more elastic behaviour which infers that the shear modulus values will be low even at reduced void content levels. Moreover, it was recommended that further experimental data for in-situ consolidation is needed for ascertaining the differences in shear modulus rate with void content. Additionally, this deduction may not be all conclusive based on the complexity of trends from the in-situ consolidation results in an increase in void content [207].

Ray et al. [208] also confirmed that the interlaminar fracture toughness for carbon fibre reinforced PEEK composites fabricated from ATL was 60 – 80% greater than composites from the autoclave process. It was opined that the high interlaminar toughness of ATL composites could partly stem from lower crystallinity shown by laser-assisted ATL when compared to autoclave fabricated composites because of the high toughness of the matrix in the ATL composite. However, there is a certain limit to optimizing the ATL process for impact toughness as the fracture toughness of E-glass fibre reinforced polymer composites was observed to be lesser than the composites derived from the hot press technique based on the work by Chu et al. [209]. Suhot and Chambers [210] explored the void effect on the flexural fatigue properties of unidirectional composites manufactured through several techniques at varying void content (1–6%). Vacuum pressure and prepregs were used to produce the samples. Through the flexural fatigue experiment, a trend of increasing void content with reducing fatigue strength was observed. Furthermore, through X-ray tomography, the shape of the voids was established to be cylindrical. Through microscopic analysis, it was determined that the presence of crack initiated from voids propagates to other voids (suggesting the voids act as crack initiating locations). However, the x-ray tomography results indicate that not all cracks are involved in crack growth.

Mehdikhani et al. [145] intensively studied the effect of the void defect on fibre reinforced thermoplastic composite mechanical performance. It was identified that the main aspect of voidage analysis lies in the quantification of their effect on mechanical behaviour. In terms of the compressive properties, the prevalent mechanism for the void effect on the compressive resistance enables the fibre kinking/buckling and other modes of instability due to the presence of free volumes and surfaces introduced through voids. It should be noted that the void scale fell within the scale features that enable fibre kinking phenomenon. This caused compressive strength to decrease by a slight percent per 1% of the void content increment. While the voids have effects on the flexural properties, the key impact is on primarily the flexural load-bearing ability of the composites which is a combination of their influence on ILSS, compressive strength, and tensile. The unique combination of these mechanisms makes it challenging to generalize the void effects. However, it was understood that a slight reduction in flexural stiffness reduction and a significant increase in flexural strength was derived from every1% increase in void content. For the effect of voids on transverse cracking, it was the collective effect of the void presence is a shift of the crack initiation strain or load, which can be substantially reduced. Although some investigations revealed that crack saturation density is insensitive to voids, some other studies opined that there is a substantial increase in the saturation density in the part with voids. The initial crack initiation is because of stress/strain concentration surrounding the voids that enable crack initiation, which in turn continues to grow in the same material as it is when it is void-free.

However, details of the phenomena are still under active investigation. This asks for reliable and precise tools for characterizing the matrix cracking behaviour to assist in ascertaining the influence of void content on crack propagation. Moreover, models of the cracking in the presence of the voids distributed in the ply are available, whilst models accounting for voids at interfaces are still to appear. The scale issue is an additional reason for the overall limited number of computational works in this area. Voids are defects that have microscopic features and interact with other micro-heterogeneities like fibre. While for the effect of voids on hygrothermal (thermal and moisture) mechanical properties, the equilibrium level and rate of moisture absorption of the composites also rely on voids. The moisture diffusion becomes non-Fickian (moisture does not move from the region of high to low concentrations) in the presence of elevated levels of voids. Void and moisture can have debilitating effects on mechanical properties since hygrothermal conditioning influences the same properties as the voids do. Hence, the degrading effect of voids on mechanical properties can be bolstered in the presence of heat and moisture, especially vital for composites that will be used in humid and/or warm conditions. However, the influence of hygrothermal mitigation on the strength properties affected by voids relies on the fibre and matrix material, loading mode, and reinforcement structure [145].

3.2.4 Creep

For the evaluation of a relatively short-term creep performance of fibre reinforced thermoplastic composite parts, Chevali and Janowski [211] studied flexural creep properties of fibre reinforced thermoplastic composites being a function of the fibre weight fraction and manufacturing induced fibre alignment. Through manufacturing, fibre length degradation was noticed with the final average fibre length being significantly reduced from the initial length. It was also observed that long fibre reinforcements reduced creep conformance when compared with neat polymer as the end final length exceeds the critical fibre length. Through radiography, the influence of the fibre alignment on the flexural creep response was ascertained, and it was confirmed that creep behaviour significantly relies on fibre alignment. It was established by Ho et al. [212] that the compression strength, modulus, and flexural properties are highly sensitive to defects that involve fibre misalignment. Furthermore, fibre misalignment was identified as the prevalent factor for failure when carbon fibre reinforced polymer is subjected to axial compression load in comparison to flexural loads where the samples are subjected to a 3point bend test in a lab setting where the principal failure mode is at 90° across the fibre axis. In addition, the effects of fibre folding within the fibre tows has a great tendency to maximize and impact the fibre alignment which hampers the compression strength.

3.2.5 Residual Stress

For the effect of thermo-residual stresses on matrix-dominant properties, thermo-residual stress occurrence will lead the matrix materials to be subjected to stretch load conditions, and the magnitude is affected by the fibre volume fraction of the composites. The mechanical such as moisture absorption capacity can be substantially affected by thermo-residual stresses. The compressive residual stress can also influence the increase of glass transition temperature. However, the interaction between the tensile and shear reduces this influence.

The upper range of temperature for the composite can be enhanced by designing the layup sequence of the parts to fulfill the required loads. It is understood that with thermal residual stresses decrease a temperature difference between the ambient and processing temperature increases through a linear relationship. Furthermore, the yield strength and elastic modulus enhance while toughness is reduced when the ageing effects alter the thermal properties of the matrix which consequently influence the liberation of thermal-residual stress [213].

For the entire structure with a focus on unidirectional thermoplastic composites, the presence of fibre poses an elevated tensile failure strain for compressive load-induced residual stress which also impacts the lateral performance of the composite of interest. If the composite is stretched across the axes of the fibre direction, the fibre strain exposed to compressive interaction creates a greater strain in relation to unloaded fibre. The unidirectional transverse tensile strength is greater than the tensile strength of the part because of the residual stresses due to thermal contraction across the thickness direction making the transverse compressive property as influential as fibre waviness from stress. The interfacial performance and stiffness of the material can also deteriorate with the occurrence of interlayer discontinuity from the residual stresses. The fracture toughness which is vital in resisting crack growth can also be influenced by delamination which can be influenced through thermal residual stresses for failure mode I and II delaminations. The residual stress can significantly decrease the fracture toughness as it distinctly reduces the strength at mode I. Additionally, the residual stress can greatly influence the fatigue performance of the structure as it generates free edge delamination [162].

Most of the reviewed studies on residual stresses focus on the manufacturing process. However, it has been established that these manufacturing conditions where localised heating is utilized can be applied in fabricating composites with complex/curved geometries such as pipes and pressure vessels [166]. Schlottermuller et al. [214] simulated internal residual stress during the filament wound process based on sub-models which were the fibre motion, rheological, kinetic, thermal, and strain–stress sub-models. It was understood that the residual stress relies on the process parameters such as the winding angle and layer numbers. Decreasing winding angle cause decreasing residual stress in circumferential direction due to reducing influence with variations in fibre volume towards winding angle direction and matrix functions isotopically. Thicker parts retain heat longer due to the ratio between the volume and surface area which leads to high residual stresses based on the combination of slower cooling rates and large temperature gradients. Furthermore, annealing from slower cooling rates resulted in reduced residual stress. This can also be attained from mandrel heating due to its contribution to temperature gradient during and post-manufacturing as cooled mandrel causes opposite stress distribution. In a subsequent study, Lu et al. [215] investigated the tape tension influence on residual stresses during composite through filament winding. A combination of theoretical and experimental approaches was applied which indicated that adjusting tape tensions is a temporary means of mitigating residual stress. When the tape tensions are kept steady, the radial residual stress becomes tensile with the circumferential radius slope being negative in the through-thickness direction. With tape tensions increment, radial residual stress turns compressive while the slope of circumferential residual stresses becomes positive and vice versa where tape tension is decreased. It is recommended that further study should focus on stress relaxation from the thermal history of the part in each layer prior to consolidation.

Through online consolidation of composite cylinders, Kugler and Moon [216] studied the effect of processing parameters on residual stress formation. It was identified that thinner wounds through low tow-tension lead to elevated residual stresses. It was also confirmed that residual stresses are influenced by the thickness and tow tension with constant cooling rates not significantly affecting the residual stresses. It was also established that the key manufacturing challenges in resolving defect formation during fabrication of parts with complex geometry are the utilization of adequately high tow-tensions and minimizing any composite/consolidating tool CTE mismatch. Based on through-thickness, Kechout et al. [217] analysed the residual stress in a multilayer composite tube experimentally and derived negative values that indicated that the residual stress present in the tube was compressive. The reduction of thickness also leads to a significant decrease in residual stress. This alludes to the observation that through-thickness and material properties are influential in residual stress development.

Eduljee and Gillespie [218] investigated the interactive effect of processing variables on filament-wound consolidated composites. The variation in the final residual stress state of in-situ consolidated and post consolidated was studied, and the interaction between the part and tool noticeably changed the residual stress state within the part. For the post-consolidated part, the mandrel raised the compressive stress at inner layers which can facilitate fibre buckling while for in-situ consolidation, winding on a mandrel leads to a significant decrease in the residual stress. Also, residual stresses were evaluated by Sala and Cutolo [219] to determine the thermomechanical effects and it was observed that where the ring was cut along the width residual stresses were released, this was also confirmed through experiments. Similarly, Casari et al. [220] characterized the residual stresses in thick filament-wound tubes through strain liberation from cutting. Moisture content and temperature influenced the mechanical behaviour of the composite and lead to stress relaxation most particularly in longer in-service conditions. It was suggested that future work should cover the influence of time-variable process pressure, temperature, and hygrothermal in-service conditions on thermoplastic composite behaviour.

Ganley et al. [221] investigated the shrinkage of curved composite parts (spring-in) as permanent deformation from residual stresses by quantifying the possible causes. Those causes were discovered to include through-thickness uniformity, part consolidation, initial curvature, and CTE mismatch between the mandrel and composite part with a tensile reduction. However, the pivotal factor was identified to be CTE mismatch that was attributed to 90% of all spring-in phenomena (involves the demoulding of a curved shell-like composite part where the angle of curvature for the part, later on, becomes smaller than the angle of its mould) while the part compaction accounted for the remaining 10% with anisotropy and through-thickness non-uniformity being negligible. In terms of the yield point of damage and plasticity Perreux et al. [222] worked on this and observed that with internal residual stress decrease, the damage yield and plasticity increase, and this confirmed that these properties are affected depending on the residual stress signs during loadings.

Additionally, Amir-Ahmadi and Ghasemi [223] studied the effect of introducing nanotubes into the fibre-reinforced thermoplastic pipes fabricated through filament winding and the mandrel diameter on the thermal residual stresses. The cooling rate was deduced to be among the most substantial processing factors influencing residual stress formation. Samples cured in an autoclave have elevated residual stresses compared to samples cooled at ambient temperature because of the appropriate timing for relaxing matrix at higher temperatures. Furthermore, a smaller temperature range that enables residual stress development and reduces temperature distribution in the middle and in the external layers. The addition of the nanotube causes a decrease in the mismatch between the CTEs of the fibre and matrix hence the thermal residual stress generally reduces in the composite. Through characterization study, the structure of the nanotube indicates sensitivity reduction of the structure to the effects of cooling conditions during the curing process, and it was also

Table 6 Possible factors on residual stress and effect on residual stress formation [204]

Parameters	Property influenced	Effect on residual stress formation
Boundary Conditions	The geometry of a composite part Heat source Liner Tape width Winding angle	The increase in the number of layers also increases residual stress
Tensions/forces	Consolidation force Tape tension	Increasing the tape force increase the residual stress
Material	Liner material Mandrel material Tape material	Glass fibre reinforced polymers as tape material decreases residual strength while carbon increases
Temperature	Annealing temperature Melting temperature Mandrel temperature	Using crystallinity temperature as mandrel temperature instead of room temperature increases residual stress
Time	Curing time Heating time Manufacturing time	When the maintained crystallinity temperature is maintained for 20 min, it increases the residual stress

observed that using the nanotubes at slower cooling conditions forms less residual stress as thermal conductivity increases which consequently prevents thermal agglomeration. In terms of varying mandrel diameters, smaller diameters induce increased residual process mainly during the manufacturing phase however, this can be negligible in terms of influence when compared to other parameters. Additionally, a thorough investigation of induced residual stress parameters experiments as observed by Schlottermuller et al. [214] summarised in Table 6. Further research showed that variation analysis (ANOVA) can always be used to determine the importance of these parameters.

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4 Concluding Remarks, Challenges, and Outlook

This study has highlighted the current state and challenges associated with manufacturing TCP and paths to defect appearances during the process. It can be deduced that the parameter selection and the material quality especially in the interlayer region are the major determinants for these defects. This study reviewed manufacturing defects related to thermoplastic composite pipes with the reinforced layer identified as a laminated structure with a dominant contribution to the TCP material behaviour. It covered specific manufacturing factors such as manufacturing processes, processing conditions, tooling, and design configuration. The manufacturing factors and defects relationship is then established and examples of how it affects mechanical properties are outlined. Furthermore, the study's key findings are described below.

The composite pipes are proven reinforced pipes of multilayers that are designed for high-level performance applications, which in comparison to metal-based pipes have high strength and stiffness to weight ratio as well as lower manufacturing cost. As a benefit of their flexibility, they are spoolable and can conveniently convey and install long pipe profiles. Bonded composite pipes are mainly categorized as RTP and TCP. Although RTP and TCP have similar materials and layer compositions, TCP is designed specifically for high-performance offshore applications. Furthermore, as TCP is fully bonded, they have certain advantages over other forms of flexible pipes due to the high fracture toughness and corrosion resistance, and great damage tolerance. TCP comprises the liner, reinforced, and coated layers that are manufactured at high temperature and pressure conditions through melt fusion bonding using the one material concept. The liner layer is extruded in a tubular profile to a winding station where the reinforced layer plies are bonded in the hoop direction and are subsequently coated for external protection and weight stability. The liner layer possesses a high yield strain which supports TCP motion by retaining the elastic range of the material and the reinforced layer is vital as it provides the load-bearing ability. Although there is fibre presence across all layers, the reinforced layer which consists of plies has the most fibre presence. The main thermoplastics polymer matrix in use are mainly PE, PA11, and PVDF which are inert materials while glass and carbon fibres are the key fibre types for TCP where glass fibre is used more because of mainly the cost-efficiency. They are deployed depending on the applications, fibres determine the pressure ratings while the thermoplastic matrix determines the temperature rating. The fibre and thermoplastic matrix also has a significant influence on the thermo-mechanical properties of the TCP.

The manufacturing phase is imperative as induced defects such as voids/porosity, fibre misalignments, and delamination/debond can be generated here which can either encourage or propagate colossal failure at in-service conditions. Automated manufacturing has now replaced manual manufacturing processes such as hand layup due to faster production rate and better reproducibility. The key automated manufacturing methods have been explained in-depth. During the melt fusion bond process of the layers, the compaction pressure and speed which determines the window of processability are restricted by the time needed for autohesion of the formed viscous matrix and intimate contact of the layers. Although the thermoplastic matrix is influenced by the processability, the cooling rate is vital to understanding their degree of crystallinity and morphology. Slower cooling rates yield a greater degree of crystallinity which correlates to a rise in compressive and tensile strength and solvent-resistance of the polymer matrix. Also, to encourage bonding, the surface roughness of the individual layers should be high, especially for curved surfaces and this signifies the need for preconditioning the layers while post-conditioning improves the surface finish quality. Void volume decreases with a slower compaction speed at lower manufacturing device temperatures while at higher device temperatures, an improved degree of bonding can be obtained even at a slow speed. However, a broader heating region increases the void level which also improves the degree of bonding, and this implies that the compaction speed can be increased. Hence, there is a direct relationship between the heated region and the heat time to determine the compaction speed. In terms of compaction force, the degree of bonding increases with high compaction force while the void content decreases. Where the compaction speed increases, the force should be increased. Although the degree of bonding increases with force, it reduces with increasing speed. Also, the bonding quality improves with an increase in the number of plies at lower compaction speeds until reaching maximum, and this reduces at high compaction speed. However, a speed increase is accompanied by a decrease in bonding and void formation and is linked to insufficient timing for the matrix to melt at the interface.

The heat source is also a vital component and they can be classified as a hot gas torch, laser, and infra-red with each heating source having its pros and cons and requiring a trade-off during design for manufacturing. The diode laser type has the most favourable heat source from this review and the other alternatives are infrared and hot gas torch heat sources as these heating devices are only suitable for a thermoplastic matrix. Successive compaction will induce degradation in the matrix encouraging void formation at the surfaces that cannot be corrected by successive layups and causing strength reduction in the final part. Through microscopic examination, higher void content was observed at lower temperatures due to weak bonding and at higher temperatures because of the long resident time that causes degradation. Also, any microcracks within the interface between the polymer matrix and the fibre can cause a major loss of strength and stiffness. Therefore, the potential of self-healing functionality and the in-situ prognosis of defects makes this subject exciting. TCP manufacturing is best described as an automated melt fusion bonding technique with the benefits of efficiency and a high-quality end product. Therefore, the essential parameters identified for optimizing automated TCP manufacturing are the compacting pressure, melting temperature, and curing time. For an automated process, prepreg tapes are placed along the predesigned path on a device surface by applying temperature and pressure. However, various defects such as bridges, gaps between the placed tapes, and both out-plane or in-plane buckling of tape. It is recommended that the nip point should be positioned in non-critical regions of the part. Certain fibre-reinforced polymers such as glass display anisotropic behaviour and the material behaviour (i.e., stress and strains) differ from that of isotropic materials. Although the anisotropic behaviour of composite materials is an advantage from a structural perspective, it can also be the key reason for process-induced deformations. For fibre misalignment/waviness defects that are vaguely defined, they occur from a marginally oversized prepreg being forced on the mould cavity. However, this is more of a design challenge which is corrected by modifying the ply size.

To understand the matrix to fibre interaction, a high molecular weight distribution of thermoplastic with the fibre can increase the mechanical induced crosslinking reaction between the polymer and the fibre, which reduces their window of processability. Furthermore, a temperature as high as the degradation temperature propels the healing of the thermoplastic matrix. However, thermal degradation severely affects the performance of the TCP by reducing the modulus and increasing the Tg of the matrix. Through crystallization, the cure behaviour of the matrix process and how it influences the material property is obtained. If the matrix cools from melting, it recrystallizes into lamellae (~ 10-20 nm thick) derived from polymer chain folding. These lamellae expand radially from the nucleation point, which forms spherulites. The phenomenon termed trans crystallization occurs where fibre is present. The two dominant mechanisms that control ILSS during ply heating are interlayer bonding and thermal degradation. For the compressive strength failure of a fibre reinforced part, the first failure mode is fibre micro-buckling which is guided by the induced fibre waviness in the presence of the ply drop. Fibre waviness during the filament winding processes may result from poor winding tension and from the local fibre micro buckling generated from the compressive load at material shrinkage from compaction using metal tools or due to volumetric variations during removal of excess resin in thick wound composite structures which includes TCP.

For pultrusion where the manufactured profile is constant, the thermal distribution and phase transitions make the manufacturing challenging to control and massively influence the quality of the end product. Herein, the material properties (i.e., elastic modulus, thermal expansion) of the matrix changes during phase transitions. Also, random in-plane waviness can emerge during the pultrusion process because of locally inadequate tow tension from the feeding spool while out-of-plane waviness is formed from increased friction. Furthermore, the difference between the ply thickness and the CTE of the in-plane lamina creates distortions that subsequently cause fibre waviness. Smaller compaction heads can induce fibre waviness due to geometric limitations. Continuous and straight fibres in the curved regions can form wavy regions or bridges overall fibre misalignment increases which forms severe wrinkling. The two key mechanisms of wrinkling formations are buckled layer and the straight layer.

Determining the critical buckling load and the minimal turning/steering radius will enable the prevention of wrinkling especially for curved parts but this should be carefully done to prevent stretching of the external fibre from lateral compressive stresses which cause transverse buckling at a specific compaction force and nominal stiffness. Insufficient matrix cures and voids are the most prevalent defects which can be mitigated by the manufacturing processing factors such as matrix viscosity, consolidation pressure, and cure temperature. Void formation and growth during manufacturing vary with the different manufacturing techniques due to changes in rheological and thermodynamic conditions during processing. In terms of growth, voids can serve as a crack nucleation site that propagates and cause uncertain failures. Also, environmental factors such as humidity have minimal effect in the curing phase. However, absorbed moisture induces a plasticization effect on the matrix by altering the mechanical and thermal properties which lower the crystallinity and glass transition temperature subsequently degrading the material and causing faster ageing. Moreover, it was earlier discerned that the void contents of the produced laminates slightly decrease with increased compaction pressure, regardless of original moisture content. This is attributed to the fibre possessing where a significant portion of the applied pressure during manufacturing and the voids are entrapped inside the laminate.

The key properties influenced by voids are the longitudinal compressive, transverse tensile, and ILSS. At the industrial level, the void content of 5% is largely accepted based on utilization. However, similar to fibre misalignments, mechanisms for the void formation and during the curing phase are vaguely known and are still yet to be fully known. In terms of prognosis, further investigations are encouraged to develop models for void contents of composites produced from different fibres and matrix systems. The cured parts may also be consolidated in an autoclave which suits the in-situ consolidation process but is dependent on the material type and manufacturing specifications. The vital parameters that define the quality of the thermoplastic matrix produced through automated in-situ consolidation are the degree of crystallinity, fibre volume fraction, and void content. Samples manufactured from automated tape placement (ATP) have a higher void volume and quality improvement in the form of better fibre distribution within the matrix and reduced misalignment when compared to the thermoset matrix sample. Through ATP, crystallization occurs when the fibre is tensioned, and this is the reason behind the improvement of fibre misalignment. Although there is improvement in fibre distribution and voids when the autoclave is utilized post-manufacturing, the autoclave cycle enabled reduced fibre misalignment which is attributed to the matrix melting during the process and it cures under pressure with unconstrained fibre. However, the autoclave cannot be used for certain matrices such as high-density polyethene (HDPE), but they can be sterilized. Void formation through ATP is influenced by defects present in tape laying such as overlaps and gaps. The melt fusion process is a complicated process that influences the geometry resulting in gaps. Continuous laying over the gap forms bridges and these gaps are defined by their width and the length along the pipe. Although gaps can be continuous between the interface of the plies, void formation at the interface discontinues it and serves as a source for delamination. The presence of voids at the interface significantly affects the ILSS of a composite structure. Gaps soften TCP and reduce its strength and stiffness which influence the fibre direction. In addition, the effect of a gap is dependent on the number of layers in similar orientation and this effect is either smaller or larger for thicker and thinner pipes, respectively.

Another key challenge in manufacturing fibre-reinforced polymer pipes is residual (thermal) stress formation. Although they are not categorized as manufacturing defects, it has a massive influence on the material strength of a part. They are introduced during the curing process and cause dimensional changes in the end cured part which can be resolved either through modification of manufacturing process parameters through process simulation or post-manufacturing. Thermal-residual stress is typically formed from processing when there is a CTE mismatch between the matrix and fibre along with the anisotropic behaviour of the surrounding laminates. They are mainly categorized into three scales which are micro-scale (fibre to matrix), macro-scale (ply to ply), and global scale (behaviour during cure) stresses. The CTE for fibre is substantially lower than the matrix both at room and melt temperatures and it is understood that the compressive stress across the axis is roughly three times higher than the stress in the radial axis. In terms of CTE mismatch, the longitudinal stiffness of unidirectional composites is extremely greater than the transverse stiffness while the transverse CTE is much lower than the longitudinal CTE. However, depending on the fibre type, the fibre can be affected by reversing the stress from the matrix. Phase changes that involve melting and crystallization are other determinants of the stress level. Also, the mould properties influence the thermo-residual stresses which are due to mechanical and thermal interaction. The annealing approach at the curing phase relaxes the residual stress and decreases the residual stress gradient which enhances the degree of crystallinity but will also increase processing time. Although the residual stress level can be negligible in comparison to fibre strength, it is still considered during the design of TCP.

For the differences in thermoplastic and thermosets, the bonding interaction between the thermoplastic matrix and fibres are Van der Waals forces indicating no chemical reaction. Fibre waviness can also occur when subjected to axial loads from residual stress as the matrix fails for a certain amount of transverse fibre and this deforms to fibre micro buckle and subsequently fibre waviness. Furthermore, delamination or crack will be created where thermal residual stress is greater than the interfacial strength that significantly impedes their mechanical properties. In service, any initiated crack tip will initially increase the yield strength and propagate into a transverse crack that reduces the load-bearing capacity. This crack density will significantly rise with the composite going through heating and ageing conditions and reduces their compressive performance. To shorten the curing time, the cooling rate and demoulding temperature should be reduced but this will cause the formation of internal residual stresses between the laminates.

Improved research on thermoplastic materials has resulted in a variety of thermoplastics that can match or even exceed the chemical and mechanical properties of thermosets which is derived through increasing the rigidity of the polymer (introducing reinforcements increases the intermolecular forces). Furthermore, thermoplastics display elastic–plastic behaviour which makes them tougher than thermosets and subsequently sustain substantial damage without physical damage or crack formation. The major limitations of the thermoplastic matrix are the melt viscosity and high processing temperature. With high melt viscosity, there will be insufficient fibre impregnation and the interface of the layers will poorly cool. The processing technique to enhance the impregnation and the consolidation is by reducing the impregnation length between the fibre and matrix. Additionally, the general objective of manufacturing high-performance composite such as TCP as pertains to material processing is focusing on efficient procedures with shortened cooling phase at a very low residence time (seconds).

There are currently two key categories of fibre to matrix defect type at the material design phase, and they are delamination in laminates and general fatigue cracks. Delamination is a critical failure phenomenon that occurs due to deterioration of the reinforcement through the thickness. This means that from layer decohesion, the delaminated surface grows in a similar pattern to crack propagation. The failure mode starts with the concentration of interlaminar stresses from voids and pores in the laminate and is typically characterized by shape, position, and area. Although delamination can be created in all laminate sizes, they are more significantly generated in thin-walled laminates. The buckling of a delaminated region reduces the compressive strength. In addition, delamination growth occurs when ILSS surpasses the matrix strength between the plies.

External pressure on TCP also causes the delaminated surfaces to be pressed onto each other and the created buckling load was negligible with slight increases in maximum fibre stress which was still 50% below the allowable stress. Therefore, buckling on TCP does not have a direct effect on mechanical performance in terms of external pressure. However, it is difficult to determine the delamination onset and the various techniques to achieve this will be further studied. Also, delamination propagation does not impede the ultimate load-bearing capacity and structural integrity of TCP, and this will require further investigation of a basic form of artificial delamination.

During the bonding phase, tensile loading conditions generate local compressive stress that encourages delamination growth close to the bonded regions. Therefore, delamination failure modes occur where the materials are subjected to tensile or tensile-compression fatigue loading conditions. Furthermore, it has been deduced that delamination growth is slightly higher with increasing temperature. Particularly for laminated composites, there are three major failure modes which are intra-ply cracking, interlaminar matrix delamination, and fibre failure which influence mechanical properties. However, delamination can be beneficial for fibre-reinforced polymers under certain conditions such as creating a stress raiser to act as stress field redistribution and also defect isolation. In terms of the effect of defects on TCP, residual thermal stress is always present in the laminate because the curing of laminate from higher curing temperature significantly influences the interlaminar stresses. Also, through manufacturing, the creep resistance can be improved by utilizing longer fibre reinforcements that exceed the critical fibre length. Hence, creep behaviour significantly depends on the fibre alignment.

Furthermore, fibre misalignment was identified as the prevalent factor for compression, and flexural failures. Where fibre folds during manufacturing, the fibre tows tend to massively affect the fibre alignment which subsequently hampers the compression strength. Treated fibre composites display higher dynamic modulus and lower energy dissipation indicating improved interfacial bond strength and adhesion between the fibre and matrix with reduced impact properties. Aligned long fibre reinforced thermoplastic polymers improve the impact, flexural and tensile properties when compared with randomly oriented long fibres. Fibre waviness can be mitigated through appropriate material selection and processing parameters. This confirms there is a relationship between material properties and processing. It is also vital to consider the material property orientation (anisotropic or isotropic) for a proper design of the final component.

Oven post-treatment of manufactured composite part increased the compression strength and ILSS as it reduces the void content and improves the crystallinity. Also, the oven post-treatment of specifically the automated manufacturing in comparison to other techniques at similar void content results in reduced in-plane shear modulus which is attributed to curing at fast cooling conditions. The key challenge with void analysis lies in the quantification of their effect on mechanical behaviour. An instance of the compressive properties is that the void affects the compressive resistance which enables the fibre kinking/buckling and other failure modes because of the presence of free spaces from voids. In addition, despite the several influential results on the void effect in fibre reinforced polymer composites, these studies have mostly covered either the global influence or local void analysis and overlooked the relationship between the two scales. This relationship is vital because as the intra-laminar display micro-scale characteristics, they can interact with other induced defects within the material which includes matrix cracks at meso/macro scale and fibre at micro-scale.

Also, nanotube addition at slower cooling conditions reduces the level of CTE mismatch between the CTEs of the fibre and matrix which reduces thermal residual stress in the structure due to the sensitivity of the nanotube structure reducing at cooling conditions. Changes in mandrel diameter are noticed to have a negligible effect on residual stress formation compared to other manufacturing factors. The presence of manufacturing defects has been identified to influence the strength and stiffness, ILSS, toughness and creep properties of the TCP. Although most in-plane failures in fibre-reinforced thermoplastics involve delamination and matrix cracks which combine to produce a fracture surface, not all failure modes involve fibre breakage and matrix cracking. However, the effect of these defects on the performance of composites has not been thoroughly understood. These challenges originate from quantifying the effect on the properties during reproducing the defects in test samples that can then be tested while maintaining material integrity and the application of appropriate monitoring techniques during testing. However, for certain applications or uses, defects are encouraged especially in stress distribution on a structure whereby artificial delamination is created.

Based on the key points deduced from this report, the scope for further work will involve the following. The investigation of the optimal heat source for enhancing the mechanisms of consolidation and how the heat transfer modes can affect specifically TCP manufacturing. An attempt will be made in resolving and providing a better understanding of thermal degradation influence on TCP manufacturing through the development of models and characterizations such as DSC, TGA, and DMTA. A laboratory-based TCP manufacturing is to be subsequently carried out and with how influential tape tensions, pull force and mould properties are during winding which encourages residual stress formation, the stress relaxation from thermal history for plies to aid the consolidation phase. The manufacturing phase will also explore the relationship between the interlayer permeability and surface roughness to improve the ILSS right from material preparation.

The key challenge with manufacturing defects is their mechanism of formation (voids and fibre misalignment), quantification (includes their sizes, shapes, and distribution), and ascertaining the fibre to matrix interaction. Hence, the next phase of the research is to explore the state of art in characterizing these defects during manufacturing, especially for curved parts such as TCP. There will be an exploration of techniques for precisely characterizing delamination and cracks which are fully or partly generated from the manufacturing-induced defects, especially for curved parts which include TCP. Through this technique, the appropriate methods can be utilized in determining the effect of the identified defects on TCP properties. This will require reproducing the defects in test samples that can then be tested and the application of suitable monitoring techniques during manufacturing and testing to observe failure onset. Another aspect that should be addressed is the interlayer strain that is produced during manufacturing and the role it serves in the build-up of residual stress.

In conclusion, this review aims to provide the current state of manufacturing-induced defects that are applicable to TCP and how the manufacturing parameters influence it. These defects have been categorized according to the scale and materials. Furthermore, this review attempted to proffer a preventative approach to these challenges with the major challenge being the conduction of suitable characterization for defect impact quantification. Hence, a subsequent review of this research will seek to determine the consequence of these defects on material performance through understanding the appropriate characterization, and process monitoring techniques. This review has attempted to bridge the gap in the literature however more investigation is required for significant improvements and sustainability in this ever-evolving subject of composite pipe manufacturing. To make progress with this research challenge, it is expected that a direct relationship between the material, property, and performance of TCP will be obtained. The end objective of the in-situ characterization is to sustainable and online approach to derive high-quality TCP with reduced defects and need for repairs, and increased production rate at safe and eco-friendly conditions while maintaining the current manufacturing process which has proven to be viable and will subsequently improve the service life of the TCP.

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Data Availability Data sharing may not be applicable to this article as no datasets were generated or analysed during the current study which is a review.

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