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OKOLIE, O., LATTO, J., FAISAL, N., JAMIESON, H., MUKHERJI, A. and NJUGUNA, J.

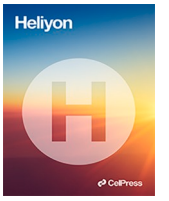
2023

Heliyon 9 (2023) e17918

Contents lists available at ScienceDirect

Heliyon

journal homepage: www.cell.com/heliyon



Review article

Advances in structural analysis and process monitoring of thermoplastic composite pipes

Obinna Okolie [a], Jim Latto [b], Nadimul Faisal [a], Harvey Jamieson [c], Arindam Mukherji [d], James Njuguna [a,e,*]

[a] School of Engineering, Robert Gordon University, Sir Ian Wood Building, Aberdeen, AB10 7GJ, UK
[b] Strohm Bv, Monnickendamkade 1, 1976 EC IJmuiden, the Netherlands
[c] Subsea 7, Prospect Road, Arnhall Business Park, Westhill, Aberdeenshire, AB32 6FE, Scotland, UK
[d] SP Advanced Engineering Materials Pvt Ltd, SP Centre, 41/44, Minoo Desai Marg, Colaba, Mumbai. 400 005, India
[e] National Subsea Centre, 3 International Ave., Dyce, Aberdeen, AB21 0BH, UK

ARTICLE INFO

Keywords:
Thermoplastic composite pipe
Manufacturing defect characterization
Real time process monitoring
Processing parameter optimization
Quality control

ABSTRACT

Thermoplastic composite pipes (TCP) in comparison to other pipes have proven beneficial features due to its flexibility which includes being fit for purpose, lightweight and no corrosion. However, during the manufacturing of TCP which involves the consolidation process, certain defects may be induced in it because of certain parameters, and this can affect the performance of the pipe in the long run as the induced defects might lead to in-service defects. Current techniques used in the industry are facing challenges with on-the-spot detection in a continuous manufacturing system. In TCP manufacturing process, the pipe is regularly monitored. When a defect is noticed, the whole process stops, and the appropriate action is taken. However, shutting down the process is costly; hence it is vital to decrease the downtime during manufacturing to the barest minimum. The solutions include optimizing the process for reduction in the manufacturing defects amount and thoroughly understanding the effect of parameters which causes certain defect types in the pipe. This review covers the current state-of-the-art and challenges associated with characterizing the identified manufacturing induced defects in TCP. It discusses and describes all effective consolidation monitoring strategies for early detection of these defects during manufacturing through the application of suitable sensing technology that is compatible with the TCP. It can be deduced that there is a correlation between manufacturing process to the performance of the final part and selection of characterization technique as well as optimizing process parameters.

1. Introduction

There is an insatiable demand for oil and gas which has led to further exploration of remote reserves. Operators currently seek to find a solution that makes projects cost-effective due to unpredictable oil prices. The concern for project and pipeline engineers is to come up with solutions that fit the capital investment budget. Also, the life cycle cost of these solutions which includes the design, manufacturing, installation, inspection, maintenance, and repair should be economically feasible. Pipes are vital in the oil and gas

* Corresponding author. School of Engineering, Robert Gordon University, Sir Ian Wood Building, Aberdeen, AB10 7GJ, UK.
E-mail address: j.njuguna@rgu.ac.uk (J. Njuguna).

https://doi.org/10.1016/j.heliyon.2023.e17918
Received 13 August 2022; Received in revised form 30 June 2023; Accepted 1 July 2023
Available online 3 July 2023

industry and are mostly metal based especially carbon steel which can be duplexed Corrosion resistant alloys when needed [1–3]. This includes the risers, flowlines and jumpers used for subsea developments which are subjected to great loads, pressures, and environmental challenges. Overall, the physical demands are limiting the efficiency of the steel-based technology which are mostly rigid pipes.

Using flexible pipes as an alternative to metal-based rigid pipes for flowlines has been presented as a cheaper solution in some cases [2]. Flexible pipes have higher strength and stiffness to weight ratios in comparison to conventional metal-based pipes. The greater the specific properties (stiffness and stress) of the composites, the ease of installation from available vessels, lower weightand in some cases also an improvement in the mechanical performance of the pipes. The combined benefits of these features can efficiently trim large capital expenditure. Although flexible pipes have a high cost for the base materials, the total cost of using flexible pipes in place of metal-based rigid pipes for offshore applications can be lower as the metal-based pipe requires more specialist installation equipment, additional end-connection pipes known as spoolpieces, and may need more replacement while ageing [4].

The key advantage of the thermoplastic composite pipe (TCP) which is a form of fibre reinforced thermoplastic composite structure over other forms of flexible pipes is a lower manufacturing cost. This is confirmed because of the lower capital intensity, simpler pipe construction and direct end-fitting design [5–7]. TCPs layers are entirely bonded and designed for high-scale performance applications. Furthermore, TCPs roughly weighs one-tenth of that for metal-based pipes. The merger of all these beneficial features makes the pipe more readily spoolable on reels, requiring smaller subsea pallets or drums. Hence, smaller vessels can be utilized in transporting and installing long lengths of TCP that enhances the economical and logistical appeal of TCP even in remote offshore facilities where using conventional rigid pipelay vessels is complex and costly. Also, another appealing aspect is that based on the melt-fusing manufacturing procedure for TCP they can be installed by terminating with end fittings onsite [7]. Composite structures are broadly distinguished through the production cost efficiency, quality of raw materials and material behaviour during manufacturing. This production cost is strongly linked to the consolidation or cooling cycle time, adaptability to changes in processing conditions (batch or continuous), reproducibility, etc. In theory, these facets can be placed in the research area of process optimization. The quality of the end component when considering TCP greatly relies on the bonding and solidification phases. Bonding induced defects (e.g., porosity and fibre waviness) or solidification developed defects (e.g., inadequate hardening/solidification and degradation) poses a risk to the overall integrity of the composite structure. Manufacturing defects can be categorized as imperfections that unavoidably occur in a usually small portion of manufactured parts of the intended design due to the faults of the manufacturing process. These imperfections are not classed as defects until their size propagates and crosses a threshold ($\leq$ 1% of structure) which is subjective but mostly in the micro scale, at this stage, they can affect the integrity and reliability of the part in the long run. Quality improvement is the field that seeks to resolve the challenge of defect elimination at the incipient stage. Lastly, the mechanisms that promote bonding and solidifying vary due to the processing inputs (e.g., geometry, material, and thermo-mechanical conditions). On the other hand, the area that emphasises on understanding the various material behaviours pertaining to process parameters and concepts can be termed material characterization and testing. Although these research fields are unique, they often interlink and can rarely be investigated by focusing on one field [8].

Based on the complexity in manufacturing the TCP through melt fusion bonding and particularly for certain processing factors, raw material or prepreg quality as well as manufacturing errors, the composite structures are rarely free from defects. These defects include voids, gaps and fibre misalignment which often occurs in the end part that subsequently impacts the mechanical performance [9–13]. Among all the defect categories that Sun et al. [13] stated occur during automated manufacturing, only the bonding and solidification induced defects as stated earlier are pivotal in TCP manufacturing and can be controllable through process optimization. Hence the defects to be covered in this review will be fibre misalignments, voids, residual stress, poor consolidation and delamination.

Our previous work has looked into the defect induction in TCP that is formed during the manufacturing process and the need to understand the material-to-manufacture relationship with the effect of the identified defects on the operational performance of TCP [14]. This review will discuss firstly the basic methods through which the processing parameters and material properties that are connected to these defects can be obtained and quantified using varying characterization techniques. This will be useful in identifying these defects at significant magnitudes within the part, albeit at the end of production. Hence secondly, for real time defect identification during manufacturing where the consolidation phase is pivotal, the various relatable process monitoring techniques will also be reviewed. Moreover, most studies on monitoring thermoplastic composites have been split into manufacturing process and in-service monitoring. This report systematically reviews the manufacturing process monitoring which is at the consolidating phase to be specific, and the progress made which is applicable to TCP.

2. Defect characterization

The shape, type and size of the composite part and the application type dictate the selection of the appropriate manufacturing process (the melt fusion bonding technique for TCP). It is vital to understand manufacturing defects as they are the dominant causes differences in material properties and possible actuators for failures at in-service conditions [15]. As previously stated, any imperfections from manufacturing are not classed as defects until their size propagates and crosses a threshold. These imperfections are classed as manufacturing defects when they have the potential of influencing the reliability and integrity of the part. Hence it is essential to identify the manufacturing types with specific strengths due to the defect thresholds [16]. Additionally, there is a substantial scrap rate generated during the production phase of a part. Defects present in manufactured composite parts are a critical challenge that can cause mayhem when applied in-service [16]. The huge production cost is another major concern for industrial applications. The presence of defects and the cost of producing composites are inversely proportional and in addition, total defect elimination is unavoidable and therefore must be utilized within a definite limit. A mechanics-based knowledge is needed for efficiently characterizing the manufacturing defects and quantifying the influence of the identified parameters.

There has been a low level of research on the contribution of the production process and their parameters to the formation of these defects in TCP as most of the research focuses on damage and failure analysis resulting from the presence of manufacturing defects in the composite structure. To substantially understand the influence of the manufacturing induced defects in the composites, several characterization techniques of the induced defects in the end parts are discussed here. Through this approach, the appropriate characterization procedures can be highlighted.

2.1. Fibre based defects

Fibre based defects can be subdivided into 3 key classifications which are fibre misalignment, out-of-plane, and in-plane waviness [16].

2.1.1. Fibre waviness and misalignment characterization

Fibre waviness can be characterized by out of plane ripples for a basic laminar with unidirectional plies. This form of waviness is common in cylindrical parts produced through filament winding. In addition, this can be similar in flat laminates with high thickness. The waviness from axial compression of fibre through non-homogenous pressure distribution between plies. Through the variation between the fibre and the environment or thermal properties of the tool material, fibre waviness can be formed. This can be categorized as either in-plane and out-of-plane fibre waviness as portrayed in Fig. 1a and b).

Fibre deviation from the designed fibre direction in a lamina plane is termed in-plane fibre waviness. This deviation from the straight plies in the flat plane is a result of fibre shifts within the laminate [16,19]. A kink of single or multiple fibre split from the laminate fibrous layer is termed out-of-plane waviness. For multidirectional laminates specifically, any fibre waviness through the thickness is noted to be a result of fibre geometry and layer bending [16,19,20]. From statistical studies, it has been observed that in-plane fibre waviness is more severe in comparison to out-of-plane waviness [16,21].

The factors related to the fibre waviness defects are the maximum deflection angle (θ), amplitude (δ), and wavelength (λ) as illustrated in Fig. 1c. The amplitude (δ) can be described as the extent of waviness formed in the laminates, while the maximum deflection angle (θ) is based on the angle from the fibre waviness to the nominal fibre direction and the wavelength (λ) is the full length of the wavy fibre within the laminates. Also, fibre waviness can be grouped into two forms which are uniform and non-uniform fibre waviness. For uniform fibre waviness, all the tows possess equal wavelength and amplitude which is scarce in the manufactured laminates but can initiate severe defect situations as the entire layers will form waves at maximum amplitude. This induced pattern includes dropping waves with different wavelengths and amplitudes. This form of fibre waviness can be easily created in lab coupons for investigating the composite behaviour when subjected to waviness. While for non-uniform fibre waviness as termed graded waviness has few plies with greater amplitude in comparison to the remaining plies. This can be further divided into firstly, the embedment where the different waviness through-thickness at uniform wavelength is present, secondly a hump where waviness is present at the top region of the laminate and thirdly an indentation for direct reduction in waviness exists at the bottom region of the laminate.

It has been established that fibre alignment affects the mechanical properties of fibre reinforced polymer repeatedly as has been demonstrated from literature; as compressive strength (longitudinal compression strength) decreases by 30% [22–24] with similar

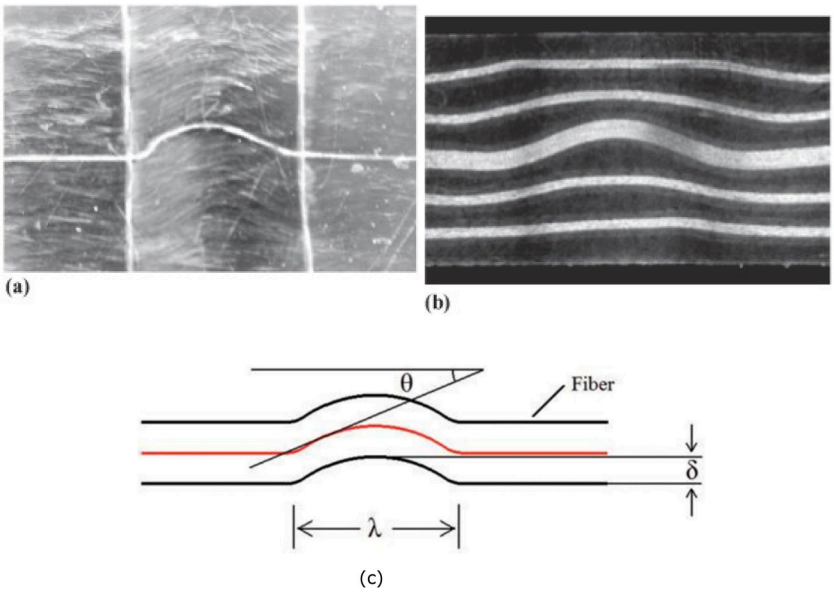


Fig. 1. Illustration of (a) in-plane fibre waviness [17], (b) out-of-plane [16,18] and (c) Fibre waviness within the laminates [16].

reductions for stiffness and tensile strength (tensile modulus), stiffness [23–26] and transverse mechanical properties [27]. The most common characterization approach for fibre misalignment induced by manufacturing was developed by Yurgatis [27]. The work focused more on measuring the fibre angle for continuous fibre composites. This was achieved through the measurement of the fibre volume distribution of the fibre misalignment angle theoretical and statistical analysis. However, the relationship between the fibre misalignment distribution and the mechanical performance was unanswered [23]. Stewart and Poursartip [23] extended on the Yurgartis approach by capturing the through-thickness part of fibre alignment from the fabricated samples. Through this, the workload for understanding fibre misalignment was halved. Furthermore, the contradiction to the hypothesis was noticed as there was no relationship between the initiation site of the prepreg and fibre misalignment distribution from using a thermal curing process with a thermoset matrix. The investigation done by Jumahat et al. [28] used both optical microscopes for examination and image analysis to successfully determine the fibre misalignment angle distribution.

Zhang et al. [29], investigated the formation of manufacturing induced fibre misalignment and breakage in carbon fibre reinforced thermoplastic composites by using optical microscopy and X-ray computed micro-tomography (μCT) as the characterization techniques. For curved samples, optical microscopy was preferred to X-ray μCT as it provides a larger view of the samples and hence gives more vital details of the fibre damage across the whole part.

Schuster et al. [30] were also able to characterize the fibre alignment of long discontinuous fibre reinforced composites through scanning electron micrograph (SEM) and image analysis. A planar orientation factor and standard deviation (statistical) analysis of the scanned regions of the fibre cross section was used to determine any deviation in fibre alignment within the structure. Through a digitizing approach, adequate data was collated to enable fibre volume fraction determination. Blok et al. [31] also used a combination of SEM and rule of mixtures (Reuss's model), to determine the fibre distribution and misalignment. It was observed that the level of uniformity of fibre distribution and misalignment affected the mechanical properties.

It is necessary to explore how fibre misalignments affect the load bearing features of the structures. To achieve this, there are two approaches to be used which are experimental testing and computer modelling. Although computer models can provide details on the influence of fibre waviness in laminates, these models only simulate an ideal form of these defects that rarely occurs during in-service conditions [32,33]. Hence, it is vital that the experimental approach be examined for a proper understanding of material behaviour and facilitate validation through the computational models, and this has been reviewed by Okolie et al. [14].

Due to the convenience of creating these defects during experimenting, out-of-plane waviness has been the subject of a significant number of studies. Normally, the out-of-plane deflection of plies is generated through introducing a thin rod in the interface between two plies during lay-up of laminate [34]. Although the result obtained is from trapped foreign material in solidified laminate, this technique creates flat samples with waviness that are adequate for damage and fatigue investigation [33].

In plane fibre waviness remains the least studied work however some procedures for introducing them at controlled extents have been generated. A cylindrical aluminium plate has been placed in a prepreg during lay-up phase. At the end of the process, the plate is flattened which causes buckling of the fibres at the top region in a still flexible laminate and the laminates are then solidified [35]. Other approaches to produce in-plane waviness have been studied such as jetting gas by dry fibres before matrix impregnation and thermally buckling fibres [33]. This procedure can cause flat coupons with uniform distribution of in-plane waviness across the composite which consequently does not conform with waviness defects noticed in real parts which are mostly localized. Therefore, this can be modified to produce localized waviness as well.

For all the fibre waviness forms to be thoroughly assessed for TCP, it is vital to characterize these defects. Past studies have focused on characterizing the fibre waviness for both waviness forms which has led to an emphasis on the measurement of the fibre orientation in the laminate [36]. The fibre orientation can then be measured through either laminate sectioning [27] or non-destructive techniques viz. ultrasound [37], radiography [38] and eddy current [39] which are covered in the non-destructive chapter.

2.2. Matrix based defects

Defects and proceeds from the induced defects for TCP to be covered here include voids, residual stresses and inadequate consolidation.

2.2.1. Voids

It has already been established that voids are among the most prevalent manufacturing process induced defects which should be identified and characterized as it is influential in determining the quality of the structure and can plausibly site of failure initiation [40]. The conventional techniques which have been utilized in characterizing voids include the following:

2.2.1.1. Immersion (Archimedes theoretical) technique. The volumetric void content is obtained through the relationship between the measured (actual) density and theoretical density of a void free composite with similar fibre content. Archimedes' principle is mostly used here to obtain the measured density. The theoretical density is to be obtained from the rules of mixture of matrix and fibre density [41]. Although this is a density-based technique which is fast evaluation technique, easy and inexpensive, it needs precise understanding of theoretical properties of the material (fibre or matrix density and weight fraction values of material) and also based on hydrophobic behaviour of thermoplastics, the void content value from these tests is inaccurate [42]. Furthermore, it can be common to obtain a negative void fraction through this technique which cannot happen theoretically [40,43]. Also, it is a destructive technique that requires that the density input be already known and barely provides another void characteristic.

2.2.1.2. Matrix burn-off. This technique involves the use of a furnace to degrade and extract the matrix surrounding the fibres which enables the determination of the fibre weight fraction. This technique is relatively convenient and requires low-cost equipment which makes it extensively ideal for certain industrial and research purposes [44]. The Archimedes method is also going to be used here to determine the measured density [40,41].

Convective currents and possible fibre degradation distort the accuracy of this method as fibre can also react similarly to the matrix. This form of error is mostly for carbon fibre reinforced materials where the temperatures to burn off the matrix lies above that of carbon fibre oxidation [43]. Chai [44] stated that the fibre should be intact and stable at a fixed temperature throughout the duration of matrix burn to salvage this challenge but the measurement accuracy from this approach remains relatively low with a minimal error of 0.5% that impedes the application of this method in low void content to a certain degree. Hence, this procedure still requires improved knowledge of the material component densities to enable the calculation of the void volume fraction for the composite sample.

2.2.1.3. Polymer matrix digestion. Similar to the matrix burn-off, but rather than undergoing thermal degradation, the thermoplastic matrix is removed from the composite through a series of chemical reactions which includes heated sulphuric acid, and the weight of the remaining sample is compared before and after testing to derive the void volume fraction. Although this is a thorough and consolidated procedure for this characterization, it takes a longer time to get the desired result and toxic fumes is generated from the chemical decomposition of the matrix which makes it a dangerous procedure [45].

2.2.1.4. Microscopy. This method is almost similar to metallography and involves the use of the light micrograph technique for determining the gravimetric void content, distribution, location, size, and shape for analysis [40,46]. The 2D image of the cross-section from this technique offers an in-depth detailing of the void morphology and matrix-fibre distribution. This can be further split into manual and automated approaches where the manual method involves the manual measurement and analyses of details obtained from optical micrographs while the automated is more advanced which incorporates imaging software and techniques to automatically analyse images and obtain statistical measurements [45]. This is a relatively quick, easy and inexpensive approach that provides a 2D morphological result. Hence, it is vastly used industrially because of the visual characterization features. However, the limitation here is that it focuses on only a smaller 2D cross section and location of each sample, therefore, involving an innate bias flaw. Consequently, this will require multiple analysis for this technique which is also destructive.

These traditional void analysis procedures just explained are not solely restricted by their reliability and accuracy, but also with restrictions from considering the final data obtained. Traditional void characterization techniques for composites are renowned for creating results with constrained precisions and poor reliability because of the innate chances of testing errors. Asides from the microscopy procedure, the others are non-visual and can only measure the general void fraction but cannot determine the individual void distribution, size, and shape. It has also been established that two laminates with similar void content can have contrasting mechanical behaviours [47], these emphasize the necessity of visual analysis. Although the vital visual details can be detected through microscopy, it is however restricted by the 2D details of the entire sample. If multiple images are not derived from significantly thin slices, it is plausible that the interconnectivity of the voids between the close slices will be missed. Ultrasonic testing which is a non-destructive void characterization technique can measure the planar size, location and distribution based on their precision, and the possibility of in-service inspection due to their portability. However, this requires a couplant agent which should be applied on a smooth and flat surface that is time-consuming and provides limited morphological results. Micro-CT is another non-destructive characterization technique for determining the void content, size, location or distribution in 3D format. This method has proven to be relatively precise and provides full 3D results. The limitation of this method is the need for small samples, focused on one location. The method can also be time consuming and expensive.

2.2.2. Residual stresses

It is known that residual stress is induced in the composites such as TCP during manufacturing at high pressure and temperatures. Noteworthy, residual stresses cannot be directly measured but through the displacement or strains in the material from residual stresses formation can facilitate measurements. Based on the reviews for determining residual stresses, here the residual stresses determination refers to both measuring and determining residual stresses. For composites, measuring the residual stresses can at certain times be problematic to achieve as the gauge systems for tensile and compressive loads are equal and in reverse directions [48]. As there is no noticeable global strain, the measurement methods will depend on the fundamental variation in the material property as a result of the necessary induction of the applied load or strain to retain normalcy within the system [49].

Selection of the appropriate measurement technique of residual stresses is dependent on whether the damage occurs on the sample or not as (semi) destructive or relaxation which is a more traditional or non-destructive technique [48,50]. The semi destructive approach relies on the relaxation principle, strains within are relaxed through partial material extraction from the part where stresses are required to be measured. It has been established that Strain or deformation measurement can be achieved using holography, laser speckle interferometry, strain gauges, digital image correlation (DIC) or Moire interferometry [48]. These traditional techniques include crack compliance, layer removal, ring core, sectioning, and hole drilling methods. One of the key limitations with the relaxation technique is the complex calculations involved as the extracted material is from an area (material preparation) that corresponds with the relaxed strains that are measured far from the prepared material location in another area [48]. Also, there is the possibility of adding more residual stresses to the material due to the machining process having some influence on the thermal behaviour of the material which can serve as a massive heat sink.

Non-destructive techniques utilize material structure contrasts to determine the residual stresses induced into the material. Magnetic, Raman, X-ray diffraction, and ultrasonic methods of measuring residual stresses fall under non-destructive methods which will be briefly discussed subsequently in the consolidation monitoring section. These techniques have the benefit of preserving the material and can be applied in enhancing product quality, in service failure monitoring and continuous structural health monitoring of the structures. These techniques need thorough material calibration to derive the necessary precise data. However destructive techniques use minor calibrations as they just cover strain or displacement measurements and are therefore used in a broad variety of applications.

Fig. 2a presents an overview of the residual stress measurement procedures considering the measurement ability of residual stresses through the thickness of the sample. The parameters worth considering during the selection of the suitable residual stress measurement are the measurement goals, damage severity, sample dimensions and geometry, measurement surrounding, spatial resolution, precision, cost and test duration.

2.2.2.1. Hole drilling method. This is the most vastly used (semi) destructive method of measuring residual stresses. This technique was first initiated in the 1930s [48]. This technique has significantly evolved with the addition of advanced drilling methods, accurate strain or displacement measuring means and enhanced computational methods. This method through strain gauges is suggested for ASTM standards. Recently, optical methods which include the DIC and Moire have been used for measuring the relaxed strains or displacements through this method for residual stresses determination. The basic philosophy for this method involves drilling a minute

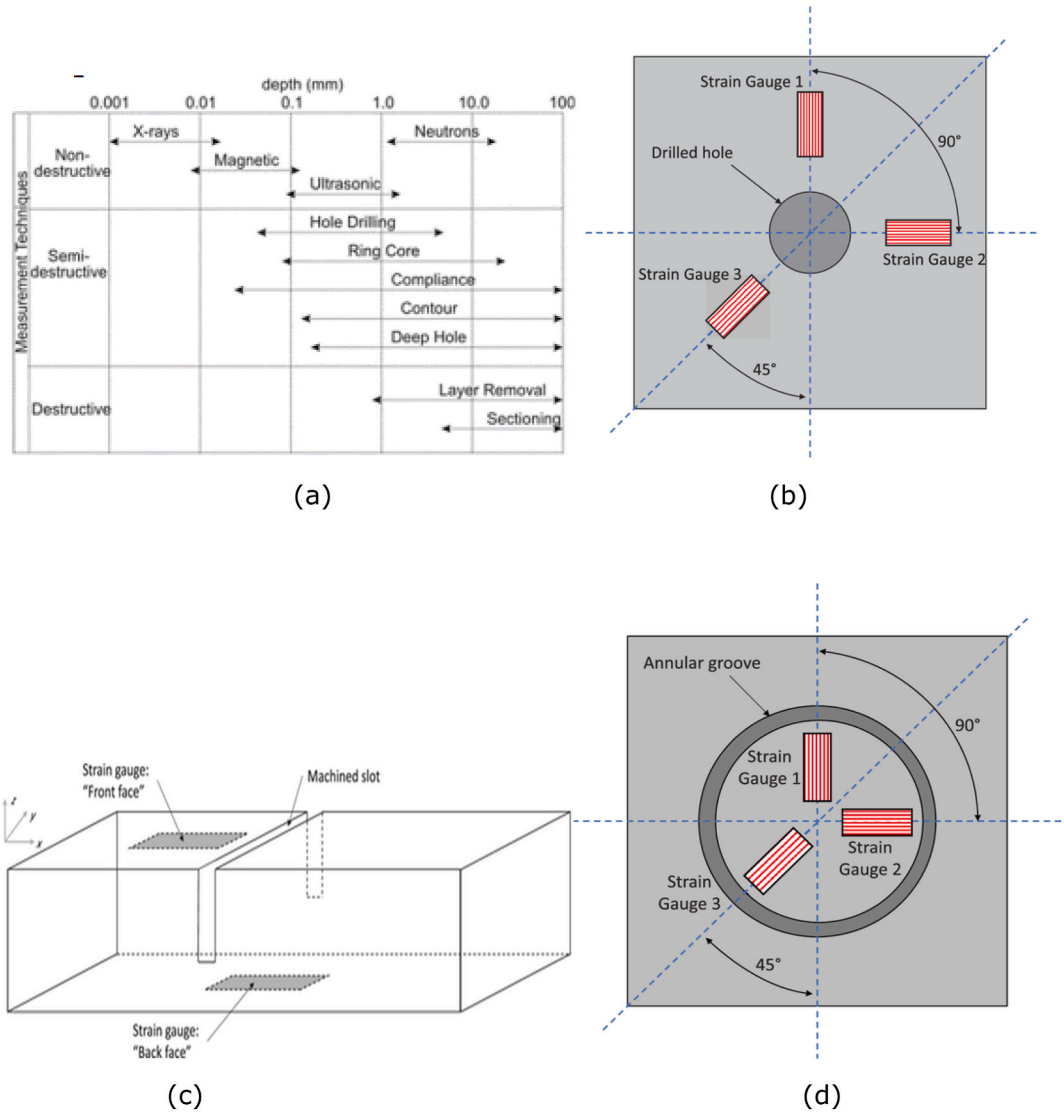


Fig. 2. (a) Comparisons for various residual stress measurement procedures and their respective penetration depth [48,51], graphical representation of residual stress measurement through (b) hole drilling method, (c) basic slitting sample and (d) basic ring core method samples [49].

hole at the centre region in the strain gauge screw (rosette) which proceeds to localized strain relaxation surrounding the hole (seen in Fig. 2b).

The relaxed strain is used to obtain the stored residual stresses in the material. Several computational means have been created to obtain the residual stresses from the relaxed strains. Previous works on residual stress measurements for laminates through this method can be subdivided into the following categories, firstly, measurements by this method through applying strain gauges; secondly, measurements using this method with the assistance of the earlier outlined optical methods and lastly the studies connected to the influence of experimental factors on measuring residual stress by this method [48].

Currently, this method is yet to be successfully applied in quantifying residual stress in fibre reinforced polymer laminates. Seers et al. [49] suggested combining this method with other described techniques herein and most especially for this method to resolve surface measurement errors.

2.2.2.2. Slitting (crack compliance) method. This method has evolved to serve as an option to the hole drilling method for measuring the residual stresses. The procedure for the strain measurement through this method is slightly similar to the hole drilling method however the difference is that this method uses a lengthy slit rather than a hole. Although the hole drilling method can measure the state of residual stresses, this method solely measures the stresses that are perpendicular stresses to the machined slit. The basic methodology for residual stress measurement through this technique can be explained by slitting the samples as illustrated in Fig. 2c.

The strain gauges are attached at the bottom and top surface of the sample with a thin slit machined close to the top gauge and directly adjacent to the bottom gauge. This approach requires narrow slit machining to be initiated from the top surface of the sample with increasing calibrations in the horizontal (x) direction while residual strains (vertical direction strains, normal to the slit) relaxed from machining is measured through strain gauges. These measures strains are then applied in determining residual stresses through the incorporation of appropriate computational systems. Most recent reviews on the investigation of the slitting method have focused on 3 key subcategories which are similar to the hole drilling method.

2.2.2.3. Ring core method. This method is also similar to the hole drilling method, for the hole drilling method the hole is created at the centre of the sample which enables the measurement of the deformation surrounding the hole. While for this method an annular channel is machined at the location of the stress required to measure as well as measuring the deformation at the centre. Basically, this method is a reversed version of the hole drilling method. The fundamental procedure for this method is portrayed in Fig. 2d.

The key characteristic of this method in comparison to the hole drilling method is that the relaxation is likely retained in strain and consequently enhances the possibility of determining the residual stresses near the actual stresses. However, for this method, the rate at which damage is introduced to the sample is roughly higher than that of the hole drilling method [48]. At the moment, the hole drilling method tends to be preferable to the ring-core method for research because of the convenience of implementing it without a specific annular drill bit or strain gauge wiring requirements. However, it is obvious that the ring core method proffers some special benefits most especially at the micro scale and further investigation into advancing this method is beneficial [49].

All these methods can be readily used for a broad range of shapes and materials and geometries with basic experimental setups using strain gauges with accurate machining. These methods have exhibited the ability of precise residual stress measurement along the whole laminate thickness which has been proven by analytical techniques. However, all methods have similar drawbacks which are firstly, the introduction of extra stresses during machining, the relaxed strains massively rely on machining factors such as the drill speed, feed and cut depth, the estimated residual stresses rely on the computational technique used and the assumed original residual stress profile. Based on all methods, the measured relaxed strain exhibits an increasing course with an increased drilled depth. Based on the procedural concept, the ring core has been observed to be less error prone as a result of the relative location of the tool and gauge. Compared to other methods, the ring core technique presents a more stable and reliable behaviour through the composite thickness. However, the damage from this method is greater compared to the other methods yet this method has more strain relaxation which consequently obtains the residual stresses that is near the actual stresses [48].

At this stage, it is mainly the key relaxation residual measurement methods through the semi destructive methods that have been described. They are other forms of semi destructive approach which may not solely rely on stress relaxation that has been validated in measuring residual stresses which are also briefly described next.

2.2.2.4. Layer removal methods. This method was original in analysing through thickness residual stresses for metallic plates [52]. This entails the gradual removal of the layer from a totally equilibrated stressed component. Hence, the residual stress is eliminated from the part and a non-uniform force distribution is generated in the system. This plate deforms to reinstate the equilibrium and the formed strain is measured which is utilized in computing the residual stress that has been eliminated. When this is continuously done through the sample thickness, a clearer image of the through-thickness differences in residual stress begins to appear [49].

For composite materials, Eijpe and Powell [53] attempted to use this method for validation however it was observed that the vital surface machining influences the material by introducing added stresses. Also recently, Gower et al. [54] gradually increased the milling of separate plies of the laminate to relax stress and observed the appearance of some visual traces from either through inadequate milling or milling into following plies. It was further recommended that the use of the present technology will be impossible for precise milling of laminates which affects the feasibility of this method. Additionally, there was a significant error from this method in comparison to the relaxation methods. However, there have been several solutions prescribed for the milling challenge such as the knife splitting, hand sanding and film embedment at intervals through laminate thickness but these solutions also have their weaknesses.

2.2.2.5. Contour method. This is a relatively modern method that maps the 2-dimensional residual stress distribution across the pre-stresses uniformed samples. The methodology involves subjecting the sample of interest to be severed to half at the location of focus. Through this procedure, the residual stress is released from within the sample and creates a slight deformation on the severed surface. A thorough surface mapping of the severed surface is produced through a coordinate measuring device. Introducing boundary conditions into a finite element model of the studied sample reinstates the residual stress induced strains or deformations back to zero which enables the measurement of the initial residual stress in the sample [49].

This method is currently prevalent within the nuclear and oil and gas industry [49,55] as an approach for measuring residual stress in welds and pressure vessels as it can generate high resolution stress maps of stresses in the normal direction to the severed surface which has been proven to have an elevated level of precision [49,56]. However, this method has some disadvantage which limits a successful application for fibre reinforced polymer composites. A reason for this is based on the impossibility of using traditional machining for the slot as it introduces machining stress into the severed surface which makes improper measurements. The adoption of the electric discharge machining (EDM) used in metallic materials for fibre reinforced polymer composites due to its significantly minor addition of residual stress during machining has limitations to carbon fibre or other forms of electrically conductive fibres and polymer matrix with conductive additives. This is because the EDM needs the material being machined to be electrically conductive which is rare for typical polymer matrix composites with glass or aramid fibre reinforcements. Although these limitations make improvement of this method bleak for composites, it is still theoretically possible and can provide a novel breakthrough for residual stress distribution across the thickness of the sample.

2.2.2.6. First ply failure method. This method can be utilized in determining the transverse residual stress present in cross-ply laminate. The methodology for this method relies on comparing the transverse tensile stress of a free unidirectional sample as the reference to an embedded stressed ply in a cross-ply laminate. An assumption is made that there is a formation of failure when crack growth is initiated within a matrix and this stress is uniform during the entire testing phase. The change in failure strengths is identified and subsequently applied in residual stress determination which causes discrepancies in strengths. Furthermore, it is assumed that it a perfectly stressed UD sample can be possibly attained through this approach and can be used as a reference. Although there is a possibility of not having global residual stress across the laminate, this may not be the same for micro stress levels as there are several complex matrix fibre interactions occurring at this scale. Hence it can be stated that this method is limited to micro level residual stress measurement [49]. Furthermore, Reid [57] recommended this method for measuring the micro-scale residual stress along the fibre alignment in the longitudinal direction. However, it was observed that the issue with the residual stress scale persists in the longitudinal direction and may not be appropriate for measuring the general micro-scaled residual stress through this method.

For further reading on the destructive methods for measuring residual stresses, Abdulkhadar et al. [48] and Seers et al. [49] have interesting reviews which are thoroughly detailed.

2.3. Interface based defect

This need for this characterization is based on the result of poor bonding at the interface either between the matrix and fibres or between the composite layers during manufacturing and these defects are often termed delamination.

2.3.1. Delamination

There are several methods for measuring delamination that has been produced in recent times through measuring the dimensions such as the area and length [58]. Previous studies have been mainly covering the maximum diameter of the delamination failure and it has been finalized that damage area is the most suitable dimension for assessing these defects or delamination [59]. Methods currently used for measuring the defects are covered next.

2.3.1.1. Visual inspection and microscopy methods. Visual defect damages through a microscope are an easier and cost-effective measurement technique being used in studies [59]. Davim and Reis [60] and Enemuoh et al. [61] have applied the tool-makers microscope in delamination measurements at the magnification of 5x and 30x respectively was used in measuring delaminated carbon fibre reinforced polymer composite materials. 10x image magnification was used by Caprino et al. [62] to ascertain the severity of a delaminated damage region in a glass fibre reinforced polymer composites where a sturdy light source positioned behind assists in visual inspection.

Scanning electron microscopes (SEM) have also been applied by researchers to derive delamination images with high magnification [63]. An instance is the study by Khan and Kim [64] used this technique in examining the drilling of carbon fibre reinforced polymer composites. However, visualization methods for delamination damages pose a challenge for opaque composites such as carbon fibre reinforced composite materials. To resolve this, researchers use varying methods for visual measurements of defects but there is no reproductive procedure when similar methods are employed which can limit result validation. Khashaba [65] was able to develop an image processing method that can measure the size of the delamination to the threshold of 10^{-3} mm accuracy. This was attained cheaply through a set of a PC (computer), colour scanner and suitable imaging software. Currently, this method has evolved to become digital and is termed digital image processing and analysis which can be used in acquiring, processing and analysis of digital images. It comprises 4 key stages which are; firstly, image acquisition which involves different imaging devices and this stage is vital for providing quality images needed for the latter stages and precise end results; secondly, pre-processing which improves image quality through noise reduction, segmentation, use of thresholds, etc; Thirdly the analysis phase for measuring the required parameter from

the pre-processed regions which assist in analysis, comparison and logic and lastly, result interpretation phase.

Currently, there is no image acquisition technique for assessing the defects. Moreover, various studies have utilized numerous techniques for processing digital images in the choice of threshold values and noise reduction as well as appropriate software methods. These techniques can provide varying defect values for the same defect damage [59].

Asides from investigating the conventional and easily accessible procedures for characterizing manufacturing induced defects, it has been established that fibre reinforced polymer composites are renowned for their high strength and stiffness to weight ratio. However, these benefits are based on the anisotropy from fibre direction while transversal mechanical properties are controlled by the low-strength matrix and matrix-fibre interface. Therefore, there will be weaker regions within the structure which raises the need for improving the transversal properties which specifically include strength would subsequently improve the durability of the composite structure. To determine any changes in material properties from modifying manufacturing parameters, the properties which influence the end material behaviour should be properly estimated through the appropriate tests and characterization techniques. These vital properties are tensile properties, compression properties, flexural strength and stiffness, interlaminar shear strength (ILSS), interlaminar fracture toughness (Mode I & II), hardness index, impact resistance, fatigue, coefficient of thermal expansion (CTE), glass transition temperature (Tg), electrical and thermal conductivities [66].

Although these defects and material properties can be ascertained through these conventional methods which can be termed destructive, non-destructive techniques are renowned for producing more reliable results and also reduce production waste. The non-destructive which is significantly garnering industrial acceptance can also be incorporated into cure and process monitoring for efficiency and will be discussed next.

3. Consolidation and process monitoring

Process control for composite manufacturing has rapidly advanced in recent years, with the vital intervention of automated

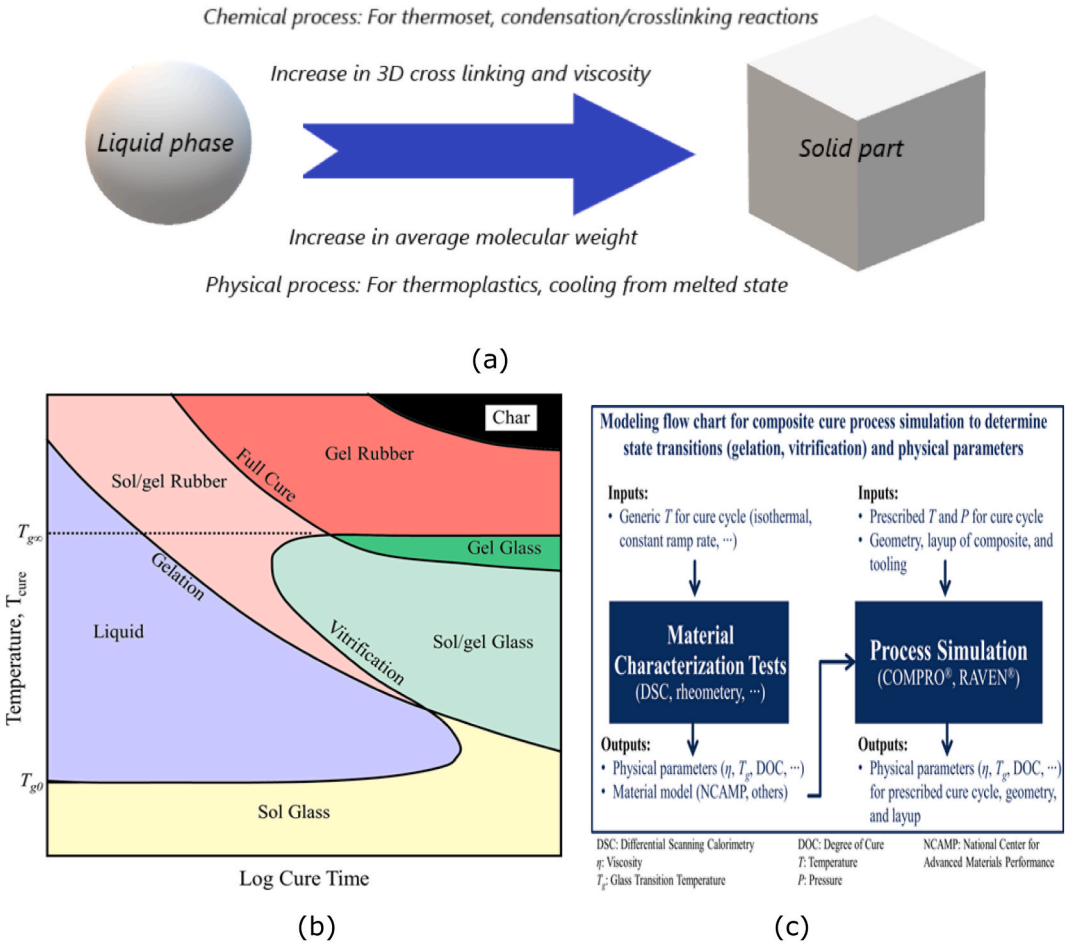


Fig. 3. (a) Basic phase transformation diagram for the matrix subjected to isothermal cure/cooling, (b) Basic phase transformation diagram for the matrix subjected to isothermal cure/cooling and (c) Illustration of modelling flowchart for composite cure (solidification) process simulation to be validated from comparing with experimental results [67].

measurements and control of process parameters such as temperature, pressure and heat distribution by the use of in-situ monitoring methods. The manufacturing process which involves heating, consolidation and curing is decisive in the formation of imperfections. As previously explained, these imperfections are not classed as defects until their size propagates and crosses a threshold which can influence the integrity and reliability of the part. Typically, curing connotes the process of converting a liquid mixture into a solid. This can be through chemical reactions or physical processes. This process is schematically illustrated in Fig. 3a.

The curing process of polymers differs based on it being either a thermoset or thermoplastic. The curing process for thermoset involves the cross linking of the polymer chains during the process to create an irreversible bond. Through crosslinking, the tendency of remelting when heat is applied is eliminated while for thermoplastics, when heat is applied it softens and becomes more fluid. However, the term curing can also be used where the thermoplastics are chemically blended or crosslinked with thermosets. The curing process for a thermoplastic polymer may not be obvious and can be termed hardening or solidified (post cooling) instead but they are reversible because chemical bonding rarely occurs. However, for enhancing the properties of the thermoplastics, the curing process will involve crosslinking which improves resistance to cracking effects from reactive substances and harsh conditions, also enhances the resistance to creep and cold flow and also resistance to thermal degradation amongst other factors. This can be achieved through irradiation techniques (heating) and chemical agents. When applied, this will interconnect the long chain of the thermoplastic molecules by forming a covalent bond which will have similar results as cured thermoset resins [68].

If the cure progresses, the molecular weight increases which coincides with the viscosity increase. A continuation of this will end eventually when the system approaches gelation and stoppage of the flow front. The number of crystals and density of the cross-links also increases until eventually vitrification is achieved [69]. For thermoplastics, the material is expected to be soft, glassy, and viscous when heated and has a cooling temperature lower than the glass transition temperature (Tg) which subsequently solidifies, and this indicates the end of the cooling phase. Here, a certain degree of curing/solidification has been obtained and this can be defined as the percentage of species to be crosslinked that are converted in comparison to a fully cured material. Once vitrification is achieved, continuous heating can lead to thermal degradation of the now solid which reduces the degree of crystallinity and a correlating loss in performance. On the other hand, an additional higher temperature post solidification heating phase can be used to increase the cross-linking and Tg while also preventing the issues arising from exotherms and volatiles related to high temperature applications. At extreme conditions, this can result in material degradation or inadequate consolidation within the same structure. With the identification of the material to be consolidated and the manufacturing process comes the optimization of the device requirements, environmental conditions and ingress of parts which can either be a continuous or discrete part production [70].

During the consolidation of a part, this can be accurately characterized in general terms through these parameters (temperature, pressure and heat distribution). However, the cooling rates of parts differ from one another even where the parts seem identical. Many factors such as the change in ambient temperature during manufacturing, the environmental condition the part is subjected to during layup and the age of the prepreg or matrix can influence the solidification time. Usually, where there is no means of directly measuring the extent of cross linking, thermoset composite manufacturers conventionally introduce a safety margin into the cure times to prevent damage that untimely demoulding can cause on a device and under cured parts. Although this will enable sufficient crosslinking, it increases the cure time and the possibility of surpassing the required processing cost. Furthermore, there is a potential risk of over curing which decreases their ductility and makes them brittle [5].

Present cure/solidification monitoring methods such as rheology, thermal gravimetric analysis (TGA), differential scanning calorimetry (DSC) and dynamic mechanical analysis (DMA) are the material characterization methods for determining the mechanical, thermal and physical properties of the matrix during the curing phase. These methods are basically conducted at small scale within a controlled laboratory set up. Hence, they are limited for in-process cure monitoring applications and will require substantial hardware adjustments for consideration [67]. A basic time to temperature plot for the polymer matrix subjected to isothermal cure is depicted in Fig. 3b portraying the phase transformations. Here Tg_{∞} denotes the glass transition temperature of the cured matrix at full cure while Tg_0 represents the initial formation at glass transition temperature (completely uncured). Gel refers to solvent insoluble and sol represents solvent soluble (ungelled).

Generally, any experimental results from cure/solidification monitoring are validated through a cure process model simulated with data of the specific cure parameters derived from experiments. From Fig. 3c, results from material characterization tests are inputs for material models which present physical parameters for basic cure cycles.

The material characterization tests are laboratory scaled test procedures such as rheology and DSC, this generates useful details on the viscosity flow and thermal behaviour of the material. Understanding these features is vital for any cure/solidification process modelling [71]. For testing composite samples, the specific layup features with the pressure and temperature values must be established. Simulation of the pristine composite sample subject to experimental conditions cure kinetics is attained through utilizing the material-specific models.

During the solidification/curing phase, monitoring real time changes occurring is imperative and here real time connotes the measurements of parameters on a timescale that enables the process conditions to be altered before the final product is completed. Presently, modern monitoring tools for real time measurements that corresponds directly to the definite chemical or physical state of the polymer matrix. Hence, this technique determines when total crosslinking or physical solidification happens which enables manufacturers to accurately predict the cure endpoint for every part. As safety margins may no longer be needed, fabrications using modern techniques can reduce cure/solidification time by 10–40% whilst also producing quality parts that are not under or over cured. This results in shorter general cycle duration and parts with better predictability on their mechanical and performance properties. These measurements are based on the consolidation time in mostly two ways which are in-line or online and their features are listed in Table 1 below.

Basically, consolidation monitoring enables the identification and detection of the several critical points or transition phases of the

curing process which includes the flow front position, state of viscosity, gelation, vitrification, degree of cure/solidification, degradation, and post solidification.

For fibre reinforced polymer composites, these transition phases help simplify the solidification process in various ways such as with matrix spread from the flow front enables adequate filling of the matrix and with interaction with the fibre, a good fibre impregnation is obtained. When minimum viscosity is attained, pressure is introduced almost immediately for void and porosity reduction which ensures good consolidation of the material. When gelation is attained flow stops and the further pressure will have no influence on the consolidation. In the vitrification phase, curing stops at the designated temperature and the part can be removed from the process and let to cool. Another option will be to monitor the early signs of degradation can be used to activate part removal. Subsequently, post solidification treatment can be further carried out on the removed part. To ensure the parts meet the requirements and specification needed for the application, the final measured degree of cure/solidification is utilized [70].

There are various induced challenges in detecting damages in composites in contrast to conventional engineering materials such as plastics or metals. A major reason for this is the anisotropy and inhomogeneity these conventional materials possess which makes them formed by one type of evenly isotropic material with known properties. On the other hand, laminated composite materials can have a broad range of material properties based on the identified matrix, fibre and manufacturing process. This can make composite modelling complex and most times non-linear. Another debacle in detection techniques is based on the differing properties of the materials such as the combination of an insulating matrix and a good conducting fibre. Lastly, often the damage occurs beneath the surface which means they are hidden most times, and this prevents the incorporation of the various detection techniques [72].

Presently a black box approach is used in the manufacturing process of composites into the finished product. This black box approach entails that time schedules are stable and also the behaviour of the material is sometimes assumed, and the process is mostly dependent on being in compliance with the required schedule of the supplier. Therefore, the fixed set of processing conditions (pressure and temperature) is followed which is based on the assumed behaviour of the material before, during and post solidification where the designated solidification times is applied while considering the quality and safety. This gives little or no room for flexibility with varying pressure and temperature or narrow safety margins or when the material ages differently. Subsequently, consolidation is the main influence of both manufacturing cost and time which can limit the efficiency of the process [70].

A major limitation of using thermoplastic composites is that the bonding force between the reinforcing fibre and matrix is inadequate during the manufacturing phase which impacts the material quality. This can be resolved through optimizing the processing parameters to ensure superb mechanical properties [73]. The in-situ consolidation manufacturing process (Fig. 4a) is most times not visible and undergoes physical phenomena that need to be understood and interpreted. Heat transfer and thermal distribution tend to be the prevalent factors which affect the process and should be understood as well as the interpretation for analysing the parameters needed for process optimization.

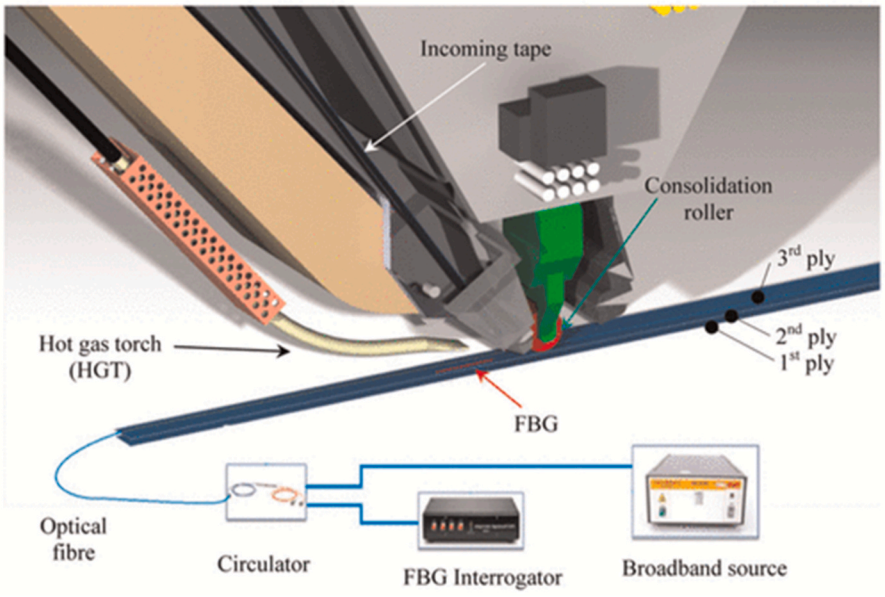
The consolidation phenomena such as residual stresses, crystallization, or intimate contact also require to be comprehended to result in the in-situ consolidation technique for improved efficiency and production (Fig. 4b). In addition, these phenomena can cause defect formation such as poor bonding or residual stresses because of the processing parameters and materials. Major contrasts between the designed and end dimensions of the composite manufactured parts are due to the generation of residual stresses in the process [75].

Consolidation monitoring is essential in eliminating the uncertainties linked to the factors used in accessing the material quality either directly or indirectly as deviations occur. This enables the appropriate corrections and modifications to be carried out to provide consistent properties and performance of the final product. Hence the goal of consolidation monitoring is to optimize both the process and general efficiency parameters [70]. The necessity of damage detection in composite is highly emphasized in comparison to plastic or metallic structures due to the load bearing requirements. Metallic parts are typically easier to model and hence they are regularly designed using damage tolerant approaches. Similarly, unreinforced plastics are not utilized in load bearing applications as their properties can be predictable and are normally cheap and simple to manufacture which makes them to be designed for easily replaceable structural parts. While for composites, their behaviour is unpredictable, and an unexpected failure of a composite part can be massively catastrophic to a structure. Although these materials are often applied in structures, advanced materials require high specific stiffness and strength. Therefore, the advancement of reliable damage detection techniques is vital to retain the integrity of the materials [72].

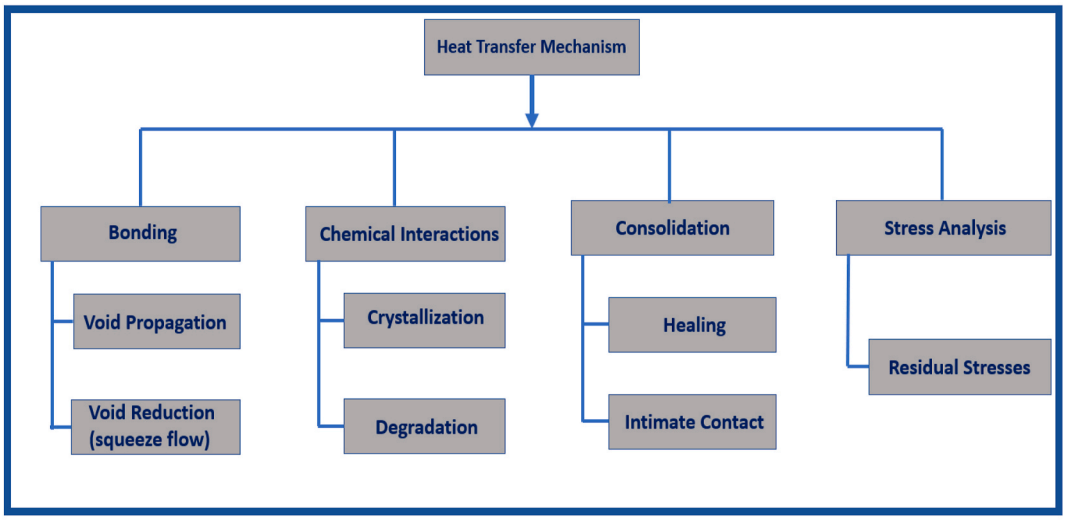
For in-situ consolidation monitoring, factors such as the internal temperature and residual strain of thermoplastic composites during manufacturing is closely linked to the final quality of the solidified material. The general performance of thermoplastic composites is substantially influenced by the residual strain; hence it is vital for real time monitoring of the internal strain of the structure during the solidifying phase. Sensors such as FBG sensors can be utilized in deriving real time variations in residual strain during the solidification. Furthermore, when the internal temperature of the structure is inadequately controlled, it leads to the incremental formation of residual strain. The easiest means of monitoring internal temperature is the thermal method but have massive

Table 1
Features of the two consolidation monitoring measurements.

In-line	On-line
No sensor integration needed	Sensors to be integrated in manufacturing process
External monitoring	In-situ (on site) monitoring
Various discrete phases in parallel production	Continuous production
Multiple production lines	Single production line



(a)



(b)

Fig. 4. (a) Experimental configuration for on-line monitoring for in-situ consolidation processing of thermoplastic tapes [74] and (b) Influence of temperature on the consolidation process [75].

shortcomings. Considering present studies, temperature monitoring through FBG seems appealing. Hence, strain and temperature calibrations need to be incorporated through the gratings for improved processing and optimization of material quality [75].

The use of sensors to precisely monitor the vital aspects of the consolidation process is necessary to provide a boost of confidence to the manufacturing process. These sensors can also be utilized as a feedback loop to control the application of pressure and temperature. Hence, embedding sensors in or around the composite provides details on the solidifying process during manufacturing and can also for integrity monitoring for in-service use [76]. Continuous real time monitoring without any time blind areas or obstructions during consolidation is crucial for regulating the consolidating parameters which eventually improves the material quality and mechanical properties of the parts [73].

Monitoring the consolidation process is ideal since this enables a degree of monitoring and control. It is invariably a necessary quality control device specific in conditions where the curing condition is undesirable. Using suitable monitoring sensors can result in rapid production of improved quality in a reproducible and repeatable basis. This is crucial in the adhesion bonding of composites where the optimal solidification conditions are challenging to attain and specifically influential to the final product [76]. Furthermore,

In-situ monitoring of the solidification process can minimize trapped volatiles, and voids as well as provision of the consolidation rate and optimization of the material properties. Previously, the curing process for composites was carried out with an empirical science approach which has advanced based on a trial-and-error strategy. Currently, significant progress has been towards investigating the process based on the results from the acquired data and mathematical models of the cure process with the goal of not solely improving the curing process but also to stabilizing and predicting the optimal process conditions. Continuous real time monitoring without any time blind areas or obstructions during consolidation is crucial for regulating the consolidating parameters which eventually improves the material quality and mechanical property of the parts [73].

Applying suitable consolidation monitoring to bonded composite structures is desirable for certain reasons such as:

a) Near difficulty to use travelling probes to ascertain solidification integrity.
b) On the first consolidation, the part is to be solidified to the highest possible mechanical integrity. Reconsolidation of the part will be time consuming and can cause further problems.
c) Manufacturing is often carried out in difficult circumstances. This includes unknown heat transfer rates and knowing that the consolidated properties will differ from the ideal laboratory environmental settings when functional.

3.1. Sensor installation

Most of the sensors discussed here focus on the localised regions within the whole component. This can limit the most popular cure sensor which is the thermocouple. During the process, thermocouples are positioned at several locations across the device and parts. A similar approach may not be viable for complex or expensive sensors.

Hence, it is imperative that sensors are used to monitor vital areas of the parts. It has been recommended that the instrumented areas which are susceptible to exothermic reaction or regions which have the tendency of being under cured. These regions can be selected based on the heat transfer of the curing part, part thickness and other vital processing factors. The right placement of sensors is crucial for their effectiveness [76].

3.2. Consolidation monitoring techniques

There are several methods and sensors which have been applied in measuring the degree of cure for composite materials either directly or indirectly through some models or calibration of the process. An instance of indirect measurement can be the determination of temperature while direct measurement can be the chemical spectroscopic composition of a matrix [76].

The sensor suitability for embedding into composites and consolidation monitoring systems will be determined based on the following criteria: (a)Cost efficiency, (b) Multi parameter sensing, (c) Efficiency in evaluating the degree of solidification, (d) The complexity, weight, and size of the device, (e) Broad range of applicability of the components and (f) Compatibility of embedded sensors in the composite part.

The implementation of multi parametric sensors is desirable for making the total number of sensors to be unobtrusive and plausible. A multi parameter sensor can be used during cure for measuring the degree of cure and simultaneously be used to measure other properties which include the temperature or strain in-service. However, the ability of the multi parameter sensor requires a significant workload from a single sensor which at times can be impossible in many cases [76]. Consolidation monitoring involves measuring the identified material properties to evaluate the degree of solidification. Basically, a significant variation in the measured property will have a response in the degree of solidification. The useful techniques for consolidation monitoring can be categorized in accordance with the material properties which are measured as a template for understanding the solidification state [70,77] and these categories are:

- Visual or Optical – refractive index, spectroscopy (FTIR, Raman)
- Thermal - temperature, thermal flux and thermal conductivity
- Mechanical – ultrasonic wave propagation, piezoelectric sensor impedance, acoustic resonance, x-radiography, fibre optic strain sensing of solidification shrinkage
- Electrical – dielectric permittivity, dipole monitoring, cross-linking voltage and heat flux monitoring

For this report, the emphasis of the monitoring techniques to be discussed are based on readily available methods which are: visual, temperature, acoustic, ultrasonic, dielectric and fibre optic strain sensing. Other techniques which are more conservative and may not be fully covered in this section are mechanical testing, DMTA, DSC and load to deflection investigation which are better suited to off-line determination of the degree of solidification in a laboratory setup.

Hence to enable improved material quality, it is vital that various processing parameters are monitored in real time, this enables each region to be adequately consolidated and the strain generated from the non-uniform temperature is as negligible as possible during the consolidation phase. Furthermore, structural health monitoring for thermoplastic composites is necessary for in-service applications to ensure they are in excellent condition. Hence, monitoring methods that effectively measure differences of the processing parameters of thermoplastic composites is vital for the application of these structures. Currently, the prevalent monitoring methods for thermoplastic composites are ultrasonic monitoring, thermocouple monitoring, optical fibre grating sensing, dielectric analysis, etc. For all these techniques, the ultrasonic technique is the most influential on the thermoplastic composite property as well

as having poor stability when exposed to high temperature surrounding. Electromagnetic field interference makes the dielectric analysis susceptible. Thermocouples solely monitor temperature and effortlessly cause severe defects in the structure. Hence these techniques may not be the best for monitoring thermoplastic composite depending on the requirements. Fibre brag grating (FBG) sensing system does not pose the same challenges described earlier and has beneficial features such as strong anti-electromagnetic interference ability, the convenience of embedding materials, sensitive signal, and light weight. Sufficient distribution of optical fibre sensing systems has certain benefits for lengthy sensing and monitoring of numerous (hundreds) of locations per meter of optical fibre. However, it is costly and has a complex structure. Furthermore, it is easily influenced by external factors that cause erroneous measurement results. These challenges can limit their suitability for thermoplastic composite monitoring. FBG sensors on their own have certain benefits which involve enhanced stability, low cost, and uncomplicated structures. Hence, it can be employed to precisely monitor the internal state of the thermoplastic composites. Comparing other elementary monitoring methods, Zhan et al. [73] presented FBG sensing as the better choice for thermoplastic composite monitoring as this method monitors the temperature and strain of the material.

3.2.1. Visual inspection methods

This is probably the most natural type of monitoring [78] where various methods of this method are already in use at several sophistication levels such as scanning electron or static optical microscope to bare optical inspection with the eye around the structure.

Although microscopy can be a functional method for deriving extensive information such as the delaminated regions or micro-crack frequency, it can also be applied in laboratory scaled research as a section must be taken out from the whole structure. Visual inspection of a structure is arguably the easiest and most inexpensive technique in comparison to the other monitoring techniques, however with damage often occurring beneath the surface, it may be challenging to identify with unaided eye. Also, using only the eye will not provide sufficient detail on the damage mode or severity. Basically, this method can potentially provide certain helpful data for damage detection, for a broader scaled structure this method would demonstrate ineffectiveness and inefficiency [72].

Micro-Raman spectroscopy is a dominant technique in industry used in determining regions of local mechanical stress in samples. This method entails the use of scattered light to examine the vibrational energy of chemical bonds in a crystalline structure. This scattered light is detected, and the features of the Raman peaks can be noticed. The peak position changes with any externally applied strain. Hence, there is a chance of quantifying the applied strain through, measuring the contrasts in the peak position between an unstressed and stressed sample.

Where the molecular orientation distribution in the polymer is determined, it will be possible to measure the strain in an amorphous polymer matrix. This is derived from measuring the angular changes in Raman peak position that relates to the applied strain. However, Raman peaks for amorphous polymers (thermoset) are slightly large and irregular in appearance while for crystalline polymers (thermoplastics) the structures are properly defined. Hence this method will be mostly appropriate for analysing micro-level strain within crystalline fibres (e.g., carbon) or for macro-level strain for crystalline matrix (thermoplastics) while for amorphous matrix (thermosets) the resolution is poor [49]. He et al. [79] used an online monitoring technique based on measuring refractive index to identify the degree of cure. This procedure entails the real time separation of the effect of temperature and cure differences on the refractive index of the composite with a step-temperature refractive index separation procedure. The curing process was a non-isothermal microwave, and the degree of cure was monitored to a significantly low measurement of $\pm$1.5% with reference to the value derived from off-line DSC measurement. This technique was categorized as promising for smart manufacturing of composite structures. Seif et al. [80] initiated a technique for measuring the delamination of carbon fibre reinforced polymer composites through the Shadow moire interferometry image concept. This technique entails projecting shadows on the sample based on a transmitter grating being visible through the same transmittance grating. Any difference in height on the sample surface carries the height details that herein indicate a defect such as delamination which creates a light and dark boundary pattern to be generated based on the length of the out-of-plane movement. Piezo-electric transducer equipment is incorporated into the optical trail to derive any phase shifting. With this modulation, 3D shapes can be measured, and the use of phase shift software creates 3D shapes with assistance from the camera images.

3.2.2. Temperature measurements

Temperature is the major elementary and basic quantity to be measured during cure/solidification process. This is an established technique which has a wide range of sensors that provides access control, robustness and sensitivity to meet contact or non-contact requirements. Usually, temperature is measured with another cure/solidification monitoring data to gauge the certainty of temperature sensitivity amongst varying sensors which is frequently used for process equipment control. Thermographic camera is now being utilized in monitoring thermal history while thermocouples and FBG sensors are vital for validation and process control.

Most times it is helpful to monitor both the environmental and material temperature to precisely identify exotherms or any other temperature reliant material behaviour that does not directly indicate changes in the environmental temperature. Furthermore, both the peak temperature and the time used to attain the peak can be applied as a template for the rationality of cure. The peak temperature derived can be used to identify the maximum rate of reaction for the material. The sensor location and the device geometry or size must be compatible for precise comparison to be achieved, this ensures that similar heat is generated and dissipated at all conditions.

The most used sensors which are industrially available are infrared or thermal imaging, resistance temperature detectors (RTDs), thermochromic coatings or paints or liquid crystal sheets (TLCs) and thermocouples.

3.2.2.1. Thermal (infrared) imaging. This technique uses a 2-dimensional arrangement of infrared (IR) radiation detectors and the

detected energy levels are converted into images by a colour scale as displayed Fig. 5a. The selection of the energy levels is dependent on the area of focus, hence the temperature range on the display screen influences the sensitivity. The IR detectors are mostly required to be used in cryogenic conditions. The benefit of this technique is that it has the capability of measuring large areas through non-contact means. Also, this technique has a single point version named IR pyrometry.

3.2.2.2. Resistance temperature detectors. This sensor is either a thin film of pure metal or wire coils. RTDs operate by incorporating the temperature dependence of the electrical resistance to the sensor metal. Typically, with increasing heat in the metal, the measured resistance also increases. This resistance is measured through the addition of current to the sensor and the resultant voltage is monitored. The most known form of RTDs is the platinum resistance thermometer (PRT). They are roughly linear over a broad temperature range and have rapid response time with resolutions of 0.1 °C. This technique also offers stability cheaper, reproducibility. However, they can also be fragile. There is a possibility for errors in calculated temperature from noise or cables mostly when length leads are used, and this can be resolved by attaching the RTD to a 4-wire bridge configuration as displayed in Fig. 5b.

The equation for converting a typical PRT which is PT100 from temperature (T) for resistance (R_T) for T > 0 °C is:

$$R_T = R_0\left(1 + 3.9083 \times 10^{-3}T - 5.775 \times 10^{-7}T^2\right) \quad \text{(Eqn 3.1)}$$

A conversion constant of about 0.385Ω/°C is obtained where R_0 is the resistance measured at 0 °C (approximately 100Ω for PT100).

3.2.2.3. Thermochromic device. The thermochromic labels and paints technique is known for colour change when above a designated temperature. This is a one time use equipment which is simple, efficient, and very affordable which thereby enables a rapid assessment of the process within the regular temperature boundaries. Thermochromic liquid crystal sheets technique has the same functions but colour changes continuously through several temperature ranges which provides a visual colour monitoring of temperature and the temperature distribution over the surface (see Fig. 5c for an example of this technique) and this device is re-useable.

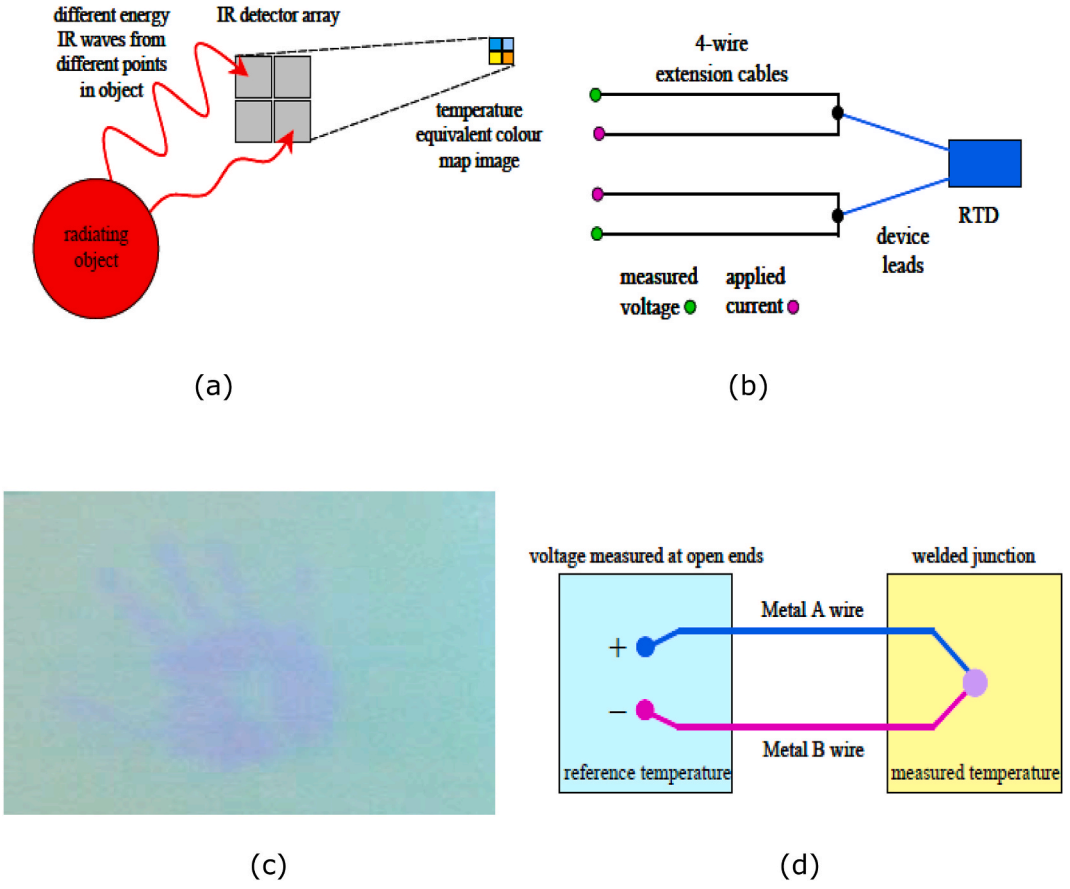


Fig. 5. (a) Elementary imaging process of the IR thermography, (b) the connection of the 4-wire bridge to the RTD device, (c) An example of a thermochromic liquid crystal sheet process. A palm comes in contact with the sheet which displays the colour changes with respect to the ambient temperature and (d) Mode of operation for thermocouples [70]. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

3.2.2.4. Thermocouples. This technique is the most used and readily available temperature sensor. They are comprised of two dissimilar metal wires that are linked together at the welded terminal. The mode of operation is based on the effect noticed on conductors with temperature gradients across the material length. A thermoelectric voltage in the middle of the open ends is subsequently generated and is in accordance with the temperature difference size between the open ends and the sensing terminal as displayed in Fig. 5d. This voltage is translated in terms of temperature if the set temperature of the open ends is known. Although the output is non-linear, their conversions are already known, and most times have an inbuilt data capturing device. The various thermocouple types which are the J, K, T, and R types have varying sensitivity and functional ranges with different weaknesses and strengths. The thermocouple type selection is to be decided based on the application requirements. Their unique advantages are their rapid response times, robustness, inexpensiveness, and they can also function at very high temperatures. Contrastingly to RTDs, external power supply is not required for thermocouples to function.

Zhang et al. [81], worked on the feasibility of fabricating a thermally responsive polymer composite which exhibits high thermofloresence and reversible thermochromism. The non-covalent behaviour of the thermoresponse mechanism enables great durability and reversibility of the composite dye system which makes this system promising. With continuous growth in this field, the cure patterns of a composite can be demonstrated in the designated dual output where temperature change is observed. These monitoring techniques can be applied in user-interactive electronic skin for health care applications [82] as well as monitoring the mechanical and thermal degradation of fibres [83]. Similarly, Yang et al. [84], have also investigated the potential of using sensors to monitor and heal glass fibre reinforced thermoplastic composites. A multi-functional interface (thermochrome) sensor was used to monitor the composite laminate under complex stress and through applying electric heating to the sensors, healing of the resulting delamination was performed. The interfacial shear strength of the laminates was noticed to have improved by 48.9% as a result of this study which is elaborately discussed in the report.

Also, Sorensen et al. [85] have been able to demonstrate the application of thermocouples and FBG sensors in the measurement of residual strain formation during the consolidation of thermoplastic composites. Through this technique, pressure and material change can be measured. Following consolidation, the birefringence or refractive index of the FBG sensors is established through a polarization control system and the dual peak spectra are correlated to the varying transverse residual strains. Modelling of the consolidation process was also carried out but faced challenges which emanate from difficulty in predicting material behaviour, precisely measuring the material properties as well as specifying the applicable boundary conditions which often gets limited due to the type of boundary condition used. Thermocouples were also embedded in the composites in an adjacent ply order for temperature compensation. To improve the accuracy of the estimated residual strain, it was recommended that the contact condition between the specimen and the mould should be adequately identified. However, the difficulty of achieving this through experiments was acknowledged. Hence, a combination of precise experimental data using FBG and the simulation of varying samples to mould contact conditions was suggested and this will provide a distinct range of feasible solutions for specific processing or material conditions.

Denkena et al. [86] examined the online AFP process monitoring from a thermal camera backed by image processing. This method was able to analyse the visible temperature differences between the surface underneath and laid-up tow to identify defects as represented in Fig. 6.

Although this system eases the task of quality inspections and significantly assists in enhancing process reliability, this system only detects defects at the surface. Consequently, internal defects and their propagation within the laminate are not captured online.

3.2.3. Acoustic resonance measurements

The mode of operation for this non-destructive technique is by vibration induction into a curing device through either exciting sound waves or by mechanical impulse. The vibration is detected by transducers and the picked-up signal is analysed [87].

The frequency spectrum of the vibration relies on the resonant frequencies which are influenced by the material density, elastic properties of curing material and the geometry of the device. Most times, the amplitude of the resonant frequency peaks can serve as a useful indicator of the material properties. There is a tendency for variations in density during curing, hence the resonance is an approximate measurement of the joint effects of the material density and stiffness. The acoustic technique is also capable of detecting failure within the bonded region of material [88].

3.2.3.1. Sound wave excitation. This technique utilizes the low frequency broadband soundwaves that is produced by a transducer

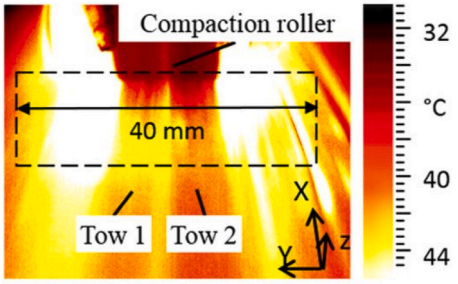


Fig. 6. The thermal imaging of the tow and the surrounding during AFP layup process [86].

which generates resonance in the cured material. A solid rod waveguide in straight contact with the cured material is used to transmit these sound waves as displayed in Fig. 7a. This signal advance along the device to the receiving waveguide setup or transducer that is located at a certain distance away.

The obtained signal is monitored, and the resulting spectrum enables the recording of the frequency correlating with the peak amplitude. With increasing material stiffness comes the increase in resonant frequency and this indicates the increase in rigidity. Through this method, an instant indication of the increase in material modulus during the cure process is derived.

This method has lesser challenges with scattering and attenuation in comparison to the higher frequency ultrasonic technique. It is very robust for industrial applications and enables waveguides access to closed mould processes. Furthermore, it proffers a parametric measurement that directly corresponds to the performance of the structure (e.g., modulus of the material).

3.2.3.2. Impact excitation. This method is mainly applied in determining the level of cure or the extent of material tolerance of the final product. The set-up for this method of a basic structure is displayed in Fig. 7b. The part is hung on thin taut wires and a little striking device is utilized to impact the structure on a specific portion. The impacted portion and the support type determine the resonant mode that is excited (flexural, torsional, longitudinal or their combination). Therefore, for exact comparisons, especially for complex structures and should be properly controlled. Identifying the supports at nodal points of vibration decreases any unneeded induced damping from the set-up. For simple structures, the nodes and vibration modes are straightforward. Impacts can be done either manually or through electro magnetically controlled tools, however, the impact must be immediate to prevent dampening any vibrations in the structure through extended contact with the impactor.

The generated sound can be captured by placing a microphone close to the structure and this goes through spectral analysis to identify the frequency and also any subsequent changes from the fixed product limits. Laboratory based curing measurements in

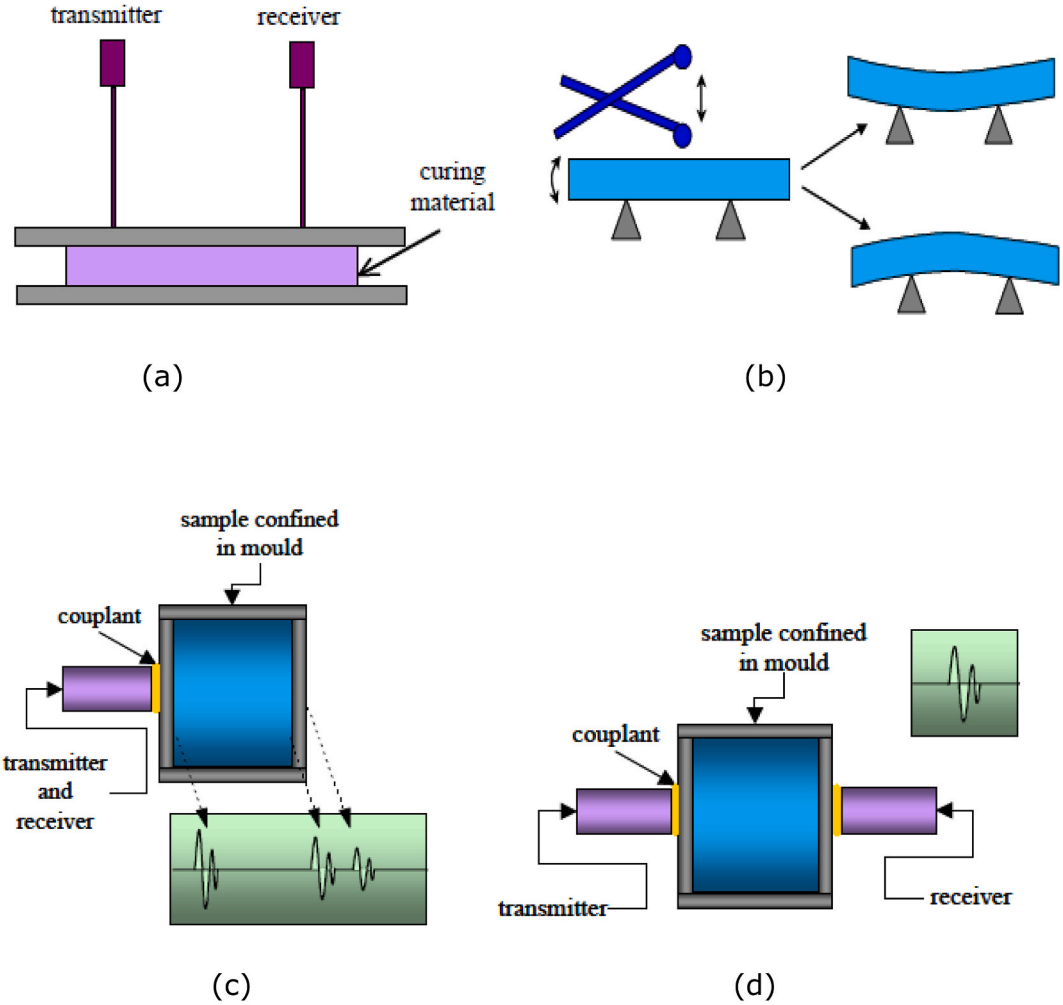


Fig. 7. (a) The acoustic cure monitoring set up for adhesive bonding, (b) basic representation of flexural vibration for a rectangular bar, (c) pulse-echo ultrasonic set up with usual received signal displaying the added reflected signals from the mould walls and (d) through transmission ultrasonic set up [70].

sample format can be carried out if the curing material is well prepared. The resonant frequency shifts higher when the material stiffens. From the gelation to the end of cure, the resonant frequency remains sensitive to minor changes in the degree of cross-linking even in fully cured structures. The resonant peak amplitudes are observed to increase while the damping properties of the cured material reduce. Although most researchers have investigated cure monitoring and their appropriate techniques, defect detection during curing has so far been insufficiently studied. The guide wave system operates at a greater frequency (within the range of low 100 KHz) in comparison to DEA and due to this beneficial feature, the potential defects can be detected [67,89].

Through acoustic emissions, studies on online assessment of delamination have been achieved. Hocheng and Jiaa [90] have solely utilized this for monitoring drilling as well as on electronic circuit boards. while Cai et al. [91] applied this monitoring method in combination with other techniques to experimentally determine the delamination damage during high-speed drilling of a carbon fibre reinforced polymer composite. However, there is not much work done on using this method for in-situ detection of defects including delamination during manufacturing.

3.2.4. Ultrasonic velocity measurements

Sound velocity in a material is reliant on the material's density and modulus. For this reason, ultrasound velocity measurements can be used for cure monitoring purposes [70]. Therefore, through the time of flight, the degree of cure can be reflected where the changes in density and thickness can be negligible. When the density is known, the ultrasonic velocity can then be applied in determining the material modulus. This may be difficult with density changing with temperature and cure behaviour hence the ultrasonic velocity is noted as a relative measure of the material properties combination.

Basically, water or any appropriate liquid serves as the couplant, however, modern non-contact methods have attempted to use air as the couplant which has been unable to achieve precise results. Asides from the cost and size of the equipment, there is also an issue with having access to both sides of the structure which signifies that the structure will be disassembled into parts for testing. Currently, single-sided ultrasonic reflective methods are in development which should serve as a solution to the challenge, however, the result quality is still not practical for monitoring and inspection purposes.

Considering the compression waves, the ultrasonic velocity (v) within the material with density (ρ) can be expresses in terms of the modulus (E) through Eqn (3.2):

$$v \propto \sqrt{\left(\frac{E}{P}\right)} \qquad \text{(Eqn 3.2)}$$

Ultrasonic velocity rises with cure progress which directly signifies that there is an increase in mechanical stiffness and density. Alternatively, both the peak amplitude and peak frequency parameters can be measured.

Using either shear or compression waves, the ultrasonic measurements can be done in two main ways which are pulse-echo or through-transmission. Although shear waves have better sensitivity to the end of cure where the final part is fully developed but it may be challenging to apply in practice hence compression waves are mostly used.

3.2.4.1. Pulse echo. This technique is based on similar principle of the time of flight for ultrasonic. However, only a sole transducer is used as displayed in Fig. 7c below. A pulse is passed across the material, and it is reflected where there is a boundary between air or mould wall and the material. The pulse may be partially reflected because of acoustic impedance mismatch. The same transducer captures the reflected signal and the transmit time is now determined.

The use of pules-echo can be restricted for high attenuation or very thick material with the reason being the pulse movement in the sample twice and in the same manner experiences signal loss twice. It is also hindered by complex reflected signals picked up from several interfaces (mainly for reinforced polymers) and interference between the transmitted and picked up signals. There are some restrictions for thin coatings where the sample signal is covered by ringing activated by exciting the pulse. However, this technique suits only when a single sided access is available. Furthermore, they are more sensitive when compared to through-transmission because it has twice the transmit time and hence twice the measured difference in time of flight. They also have lower equipment costs.

3.2.4.2. Through transmission. This technique needs two transducers to be aligned collinearly. A spike in voltage is generated from an electronically excitation unit which activates an ultrasound pulse from the transmitting transducer. The pulse moves from the material and is picked up by the second transducer as displayed in Fig. 7d. The picked-up signal which can be amplified is subsequently captured and shown on a PC. A unique characteristic of the pulse is the use of a baseline crossover to time the movement of the ultrasound from one probe to the other. This timing will need to be settled to roughly 1 ns to enable the needed sensitivity for cure monitoring. These measurements are reproduced at frequent intervals during manufacturing to create a direct link that relates to the material properties all through curing. For the advancement of this technique, it can become automated.

The availability of coupling devices and efficient high temperature transducers facilitates the use of this method for high temperature applications. For this scenario, the system requires calibration for the changes in the transducer's reaction with temperature. The addition of transducers into the walls of the device that are small parts (a few mm) of the material enables the use of this method in enclosed processing conditions. The transducer diameter, power and frequency determine the maximum attenuation or thickness of the material to be evaluated.

3.2.5. X-radiography

Although these techniques are relatively easier and inexpensive to incorporate and interpret, they need heavy and expensive

equipment that is challenging to use on large structures with taking a section out. The main challenge of this method in applications is that it requires access to both sides of the surface so as to emit and retrieve the radiation which most times is not realistic. Chen [92] used the X-ray non-destructive testing technique for examining the delamination in CFRP materials. To enhance the contrast between pristine and damaged regions of the part, the part of interest is coated with a radio-opaque chemical and proposed the combined use of radiography and X-ray for defect evaluation.

Tsao and Hocheng [93] have applied X-ray medical computerized tomography for assessing drilling-induced delamination in several carbon fibre reinforced composites. Ochôa et al. [94] propagated ultrasonic guided waves in ultrasonically welded thermoplastic composite joints with the aim of understanding the influence of weld manufacturing on defect formation through guided wave transmission along the joint. This was a ground-breaking investigation which enabled the establishment of a strategy for diagnosing manufactured defects from ultrasonic welded thermoplastic composite joints. Reichle et al. [95] have used air-coupled ultrasound for a non-contact quality control of the thin composite material manufacturing process which was pultrusion. The pultrusion process was altered to induce artificial defects into the pultruded bar to assist in testability through the air-coupled ultrasound. Through this investigation, there is a potential evaluation of detecting defects with the air coupled ultrasound system however, this depends on the defect type.

Tackitt [96], developed through transmission ultrasonics (TTU) as a non-intrusive means of process monitoring for online control during thermoplastic fusion bonding manufacturing. The material properties identified as vital for the study are the temperature dependence on ultrasonic attenuation and sound velocity. Consequently, experimental systems based on using both pulse-echo and laser ultrasonics in through-transmission were adopted in characterizing the properties at temperature roughly 330 °C. Generally, through this technique, a near linear relationship was derived between TTU amplitudes and weld strength which signifies potentials for on-line, non-intrusive monitoring technique for weld strength. Jost [97] was able to visualize the temperature and melt state of thermoplastics and established a relationship between material temperature and sound velocity through time-of-flight monitoring from the ultrasound technique. This is vital for understanding material behaviour from the use of ultrasonics and can address the thermoplastic behaviour during solidification from melt fusion bonding manufacturing. An ultrasonic B-scan based on time as displayed in Fig. 8, demonstrates the details of both the melt phase and approximate temperature of the material. From the B-scan visualization, valuable details for making informed decisions for the manufacturing and quality control processes for thermoplastic matrix composites.

Chadwick and Willmeroth [98] intentionally introduced defects to an AFP unidirectional laminate so as to detect defects through in-process monitoring and post manufacturing ultrasound scans. These inherent defects included foreign material inclusion (aluminium), weak consolidation from poor heating, missing tow materials and charring or thermal degradation from overheating. Thermal camera on defect visibility was the in-process monitoring technique utilized here via the temperature readings which was followed by ultrasonic scanning of the final part. The thermal camera indicated sound detection of the weak consolidation, missing tow materials as well as the non-uniformity of the substrate surface as a result of degradation during layup. However, this technique failed to detect temperature changes from the inclusion of aluminium, and this was attributed to the size not being large for detection and this influenced the temperature output. However, the ultrasound scan was capable of detecting all defects within the laminates through the combination of time delay – based and amplitude based calibrated displays which enabled better visibility. A recommendation on quantifying the minimum detectable size and enhance it through changes in temperature averaging function. This investigation revealed that the combination of both techniques can be categorized as robust albeit with some improvements, especially for the in process monitoring such as increasing the resolution of the output temperature values to enable the detection of smaller sized foreign inclusions.

Han et al. [99] attempted to experimentally detect the effect of internal defects on stress distribution during automated manufacturing. Void content of the prepreg sample was the internal defect to be examined, it was quantitatively estimated through a relative model between it and an ultrasonic attenuation coefficient which is displayed through a photographic procedure from the optical microscope and an A-scan ultrasonic flaw detector (before and after solidification (Fig. 9a)). This facilitated the void content estimation at various processing parameters, the link between the consolidating force and defect distribution was obtained which includes the void content, defect amount and the maximum defect diameter. If other processing parameters are constant, the result indicated that the majority of the void content reduces with consolidation force increase. Although there was no noticeable link

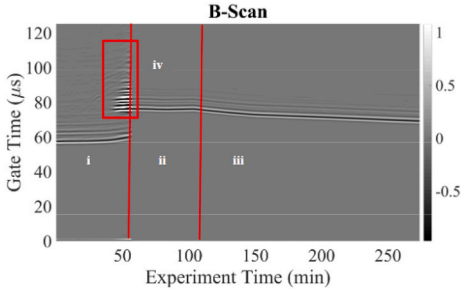


Fig. 8. Ultrasonic B-scan of a thermoplastic polymer wax based on time. The melting signal is noticed advancing in region iv. Regions i, ii and iii represent the heating, constant temperature and cooling regions respectively [97].

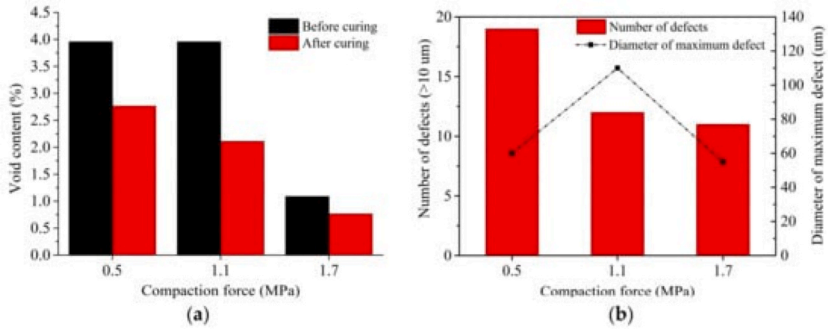


Fig. 9. The plot depicting the relationship between consolidation force and defect distribution (at temperature of 40 °C and speed of 20 mm or s during layup) (a) void content (b) maximum defect diameter and number of defects [99].

between the consolidation force and the maximum defect diameter, the number of large-diameter defects that are closely linked to the consolidation force indicated a negative correlation (Fig. 9b). Also because of the wave scattering and stress concentration surrounding the defects, the part with elevated void content can dissipate more energy during stress wave propagation.

An improved method for improving wave velocity measurement was suggested as this will facilitate the establishment of online real-time detection and control procedures for internal defects dependent on the stress wave features. Ibarra-Castanedo et al. [100] were able to investigate defects in glass-reinforced (glass laminate aluminium reinforced epoxy (GLARE)) fibre metal laminates but experienced some difficulty with obtaining precise defect detection through this method due to glass fibre reflecting the ultrasound waves.

Ultrasonic inspection has been extensively used in the characterization of voids in composite. Stone and Clarke [101] studied the link between the voids in composite materials with the attenuation and speed of ultrasound. From the study on unidirectional composite panels of uniform thickness displayed that there is a bi-linear relationship of ultrasonic attenuation with the void content. In addition, it was discovered that the interlaminar strength reduced with void content increment. For void morphology characterization, it was deduced that where the porosity is less than 1.5%, the voids were mainly sphere shaped with a diameter of 5–20 μm because of the volatiles and the void size increases with increasing porosity. On the other hand, when the porosity was greater than 1.5%, the entrapped air between layers starts dominating these voids is flat and expands in the fibre direction, with a size significantly larger than that of the voids created by the volatiles.

Kas and Kaynak [102] applied the ultrasonic C-scan technique to study the RTM manufacturing process, specifically the effect of injection pressure. Panels manufactured at an injection pressure of 2 atm was noticed to have better mechanical property. The results indicated that when the injection pressure is greater than 2 atm, the amount of voids increased (100 to 1000 μm) which decreased the mechanical properties. This is attributed to the change in the flow rates between fibrous yarns and around the fibrous yarns. At elevated injection pressure, the macroscopic flow around the fibrous yarns begins to predominate, leading to induced voids from nonuniform flow fronts. Fig. 10a depicts the ultrasonic C-scan image of composite panels with voids [102]. It was observed that if a suitable segmentation method is utilized, the derived porosity value indicates slight reliance on the size of the voxel size as well as other CT scanning factors.

Nikishkov et al. [39] evaluated the accuracy of voidage quantification using X-ray CT. In a bid to reduce measurement errors of the void contents, a density-based contouring technique was developed to partition voids to the sub-pixel resolution (an example of void segmentation through this approach is shown in Fig. 10b), and the results from optical microscopy and X-ray CT portrayed a good correlation in carbon fibre-epoxy systems. Based on the 3D features of manufacturing defects, the quantification of the voids through 2D techniques is not reliable.

Kastner et al. [103], noticed that CFRP samples that possess relatively low void content have more spherical voids, however with elevated porosity (>3%) samples the voids appeared larger and flat. In addition, the voids were unevenly distributed within the sample, with several voids localised in some layers. Little et al. [41] also found that with void content increment, the geometry of the large voids varied and is more expanded with minor distribution of spherical voids across the entire sample, as can be seen in Fig. 10c.

Certain level of progress has been achieved in visualizing the void formation during the manufacture of composites from prepregs. The work by Centea and Hubert [104] demonstratedthe use of X-ray tomography to study the development of voids in out-of-autoclave solidified CFRP. The composite panel was manufactured through woven pre-impregnated materials which obstructed the cooling cycle at several stages. This work deduced that the variation in distribution and volume of voids during the consolidation cycle was noticed. Fig. 11 (a-c) depicts the volume rendering at various consolidating phases and herein, ellipsoid 'bubble' shaped voids were observed in the final consolidated sample.

However, there is still a challenge in studying void formation in the LCM manufacturing process. Resolving this challenge has been garnering interest from researchers [105]. Unfortunately, there has been no other substantial breakthrough that has been published so far.

3.2.6. Dielectric measurements

This method measures the degree of cure through the measurement of the conductivity of the small and polarised ions and any

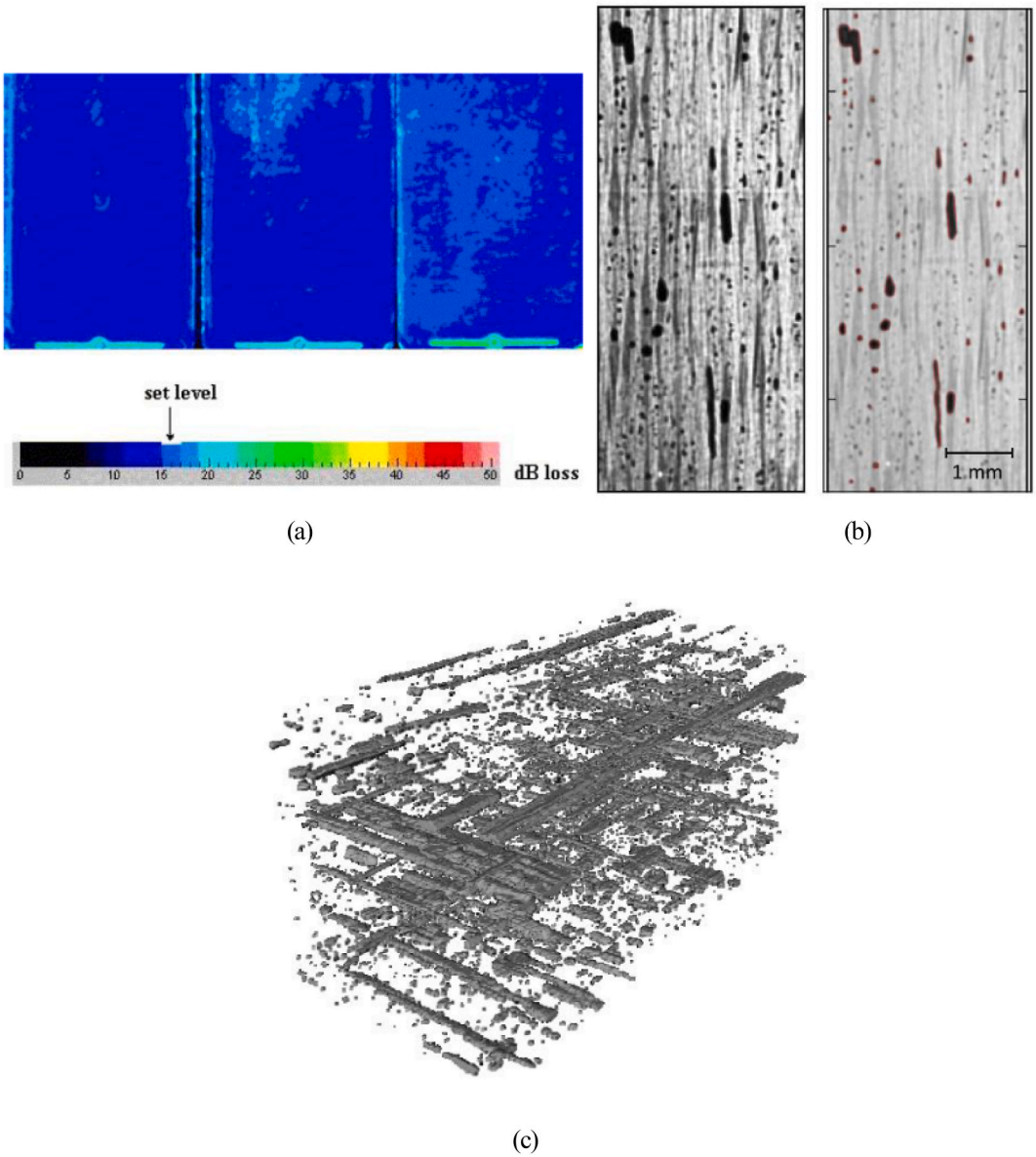
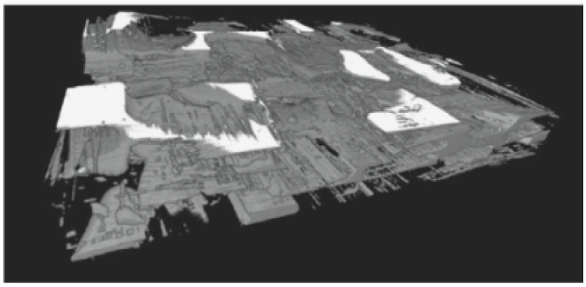


Fig. 10. Ultrasonic C-scan for three composite plates moulded at resin injection pressures of 2, 3, and 4 atm with voids present where the decibel (dB) loss is represented by the colour spectrum [45,102], (b) Depiction of the choice voids outlined in red [39] and (c) 3D rendering of void content in CFRP sample [35,45]. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

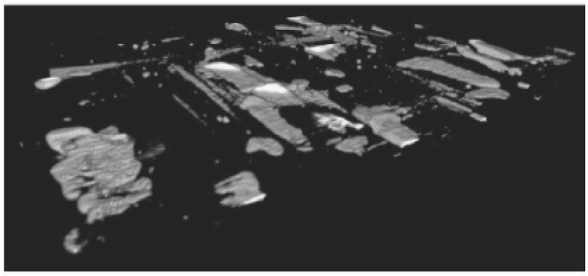
other impurities that reside within the matrix. Ions tend to move from an electrode of contrasting polarity. However, the speed of the ion mobility is restricted by the viscosity of the matrix. As cross-linking progresses during cure, the viscosity of the matrix increases with a correlating decrease in the ion mobility rate. Hudson and Yuan [67] stated that cure monitoring techniques such as dielectric analysis (DEA) have been able to perform in laboratory settings and it is expected that DEA principle can potentially be implemented at a larger scale for in-situ consolidation monitoring.

The mode of operation for this technique involves the measurements using two electrodes that are connected to the device through conductive cabling. Generally, the electrodes are embedded in the uncured matrix and placed at short distance from one another with a small matrix filled space between them. The electrodes are made from either ceramic or metallic materials and they comprise of either firstly, interdigitated combs where a two-comb shaped flush-mounting the electrode within the part or on a non-critical surface or secondly, parallel plates that measure the bulk ionic conductivity across the thickness of the composite part. Both mounting methods for the interdigitated comb provides a similar degree of precision albeit the part embedded sensors must be integrated into the layup and end up being non reusable.

For ion conductivity measurement, AC voltage is added between the two electrodes at frequencies typically within the range of 0.1



(a)



(b)

(c)

Fig. 11. 3D rendering of the void content propagation during the consolidating process [45,103].

Hz–100 KHz. The phase and amplitude of the response frequency is generated from the sensors as a result of ion mobility can be used to derive the ion conductivity. Some dielectric monitoring tools measure the reduction in ion conductivity and directly calculate the viscosity increase. Other tools measure ion resistivity or impedance (the conductivity inverse that is proportional to viscosity). Hence, dielectric sensors can be utilized in linking the ion conductivity to the minimum viscosity and gelation onset and also the glass transition temperature of the cured matrix. With this novel knowledge, the moulding temperatures and material formulation can be adjusted and the parameters for moulding parts can now be optimized.

For carbon fibre reinforced parts, carbon has a tendency of interfering with the precision of measurements as they cause short circuiting (electrons stray from the established pathway of the electron circuit) due to the conductive properties of carbon fibre. A solution of using a special glass filter cloth to isolate and insulate the sensing area has been suggested [5].

Basically, this method applies electrodes to contact the matrix to monitor the propagation of the intrinsic electrical properties of the material which occurs due to physical and chemical changes during the cure process (e.g., Tg and viscosity). The mode of operation is the measurement of variation of the current and voltage between the pair of electrodes. This technique is supposedly the most suitable for detecting all the vital stages during cure, regardless of the complex features of dielectrics and the unknown potentials in how relevant they are to process parameters.

The use of sinusoidal voltage on a pair of electrodes forms a localised electric field. This induces dipole rotation and ion movements within the matrix creating the sinusoidal current. These movements can be hampered by a viscous drag; this results in a phase difference between the stimulated current and the applied voltage as depicted in Fig. 12a.

The redistribution and reorientation of the charges only happen where the charged species are adequately mobile to respond during the frequency or timescale of the excited field. Through measuring the associated voltage and current at orderly intervals and various

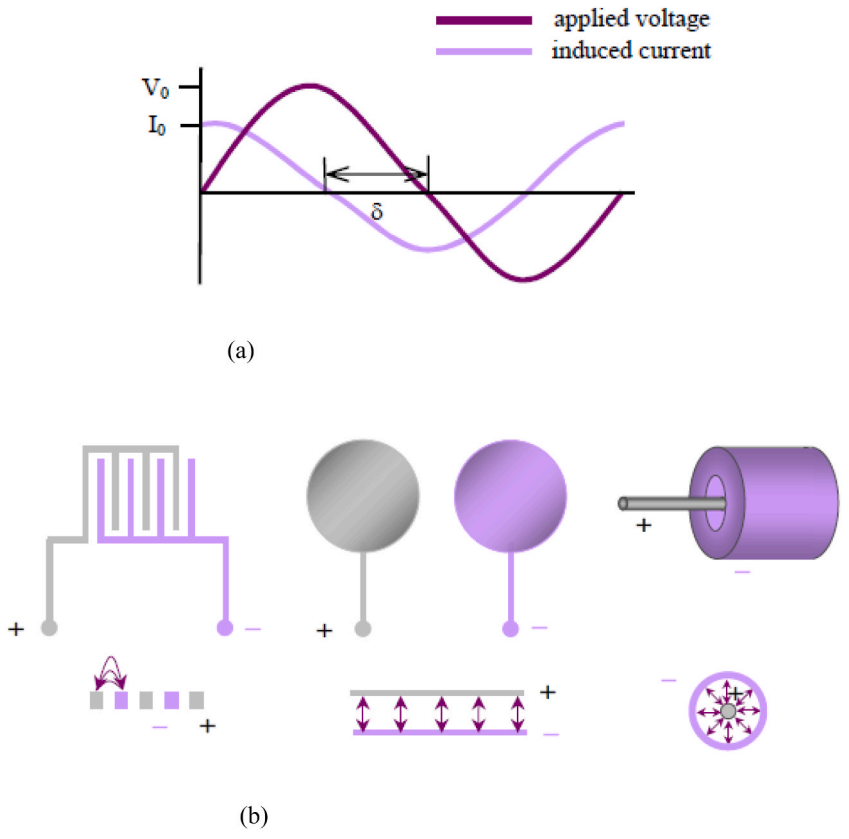


Fig. 12. (a) Phase and amplitude relationship between the induced current and applied voltage response and (b) basic dielectric sensor set up and their subsequent electric fields. The interdigitated at the left, parallel plate is at the middle and coaxial is right [70].

frequencies as cure develops (can possibly be within a large range of 10^{-4} - 10^{-11} Hz), hence the variation in capacitance and conductance of the polymer can be ascertained.

The electrical properties of the matrix can be expressed in several ways based on the current (I_0), measured voltage (V_0) and phase shift (δ). The major simplified method is the intricate impedance Z. This details the electric resistance and hence it is made up of the phase angle information. Z is obtained by (' - indicates the "real" part or the in-phase response and'' - indicates the "imaginary" part or the 90° phase-shifted response):

$$Z = Z' - Z'' \quad \text{(Eqn 3.3)}$$

$$|Z| = \sqrt{(Z_2' + Z_2'')} = \frac{V_O}{I_O} \text{ and } \frac{Z''}{Z'} = tan\ \delta \quad \text{(Eqn 3.4)}$$

This is then converted to dielectric permittivity (ε) which connotes the material's ability to store charges from the applied field [106][104], through:

$$\varepsilon = \varepsilon' - i\varepsilon'' \quad \text{(Eqn 3.5)}$$

$$\varepsilon' = \frac{-Z''}{\omega C_O Z_2} \text{ and } \varepsilon'' = \frac{Z'}{\omega C_O Z_2} \quad \text{(Eqn 3.6)}$$

Here A/d is the cell constant which relies on the electrode spacing, ε0 represents the permittivity of vacuum (8.854×10^{-12} F/m) and $C0 = \varepsilon 0$ A/d signifies the vacuum geometric inter-electrode capacitance of the cell.

The theory for this method is the use that the dielectric data interpretation relies on the specific behaviour of the investigated material, and this may change between the initial and later cure phases. These behaviours are first, the ionic components which dominate at low viscosity and low frequency an example is pre gelation and also at high temperature and secondly, the dipolar components which dominate at high viscosity and high frequency an example is the gelation phase.

3.2.6.1. Dielectric sensors. There is various electrode set-ups that are presently available as can be seen in Fig. 12b above. The main

basic types are the bulk sensor or parallel plate and inter-digitated sensors.

The parallel plate sensors are solid regions of metallic electrodes placed on an insulated panel. This generates a uniform electric field between the plates of contrasting polarity. Interdigitated sensors can be described as a sole surface with comb like metal-based electrode patterns that are printed into a little and thin insulating substrate layer. It generates localised fringing fields between adjacent fingers of contrasting polarity, and this propagates into the matrix to a length that is dictated by the electrode spacing or geometry.

Dielectric sensors can either be reusable or implanted and embedded for internal measurements or placed externally for surface measurements. Furthermore, they require protection from short circuiting against any conductive part in the material an instance is carbon fibre reinforced polymer matrix or metallic particulate fillers. However, they must stay in intimate contact with the matrix during manufacturing. Presently, there are durable sensors which can be mounted as an integrated component of a mould device wall. These sensors are linked to an impedance analyser which is utilized in performing electrical measurements that spans a broad frequency range whereby data collection is carried out at frequent intervals during the cure cycle.

3.2.7. *Dipole monitoring*

Although ionic conductivity is the dominant electrical property utilized in dielectric measurements at lower frequencies, an alternative approach for cure monitoring here will depend on the monitoring of polar molecules with regards to each molecule and they are called dipoles. Dipoles are in pairs which are found in the matrix, and they are the determinant in the electrical response of the matrix at higher frequencies. Based on this knowledge, the Time Domain Reflectometry (TDR) system was developed by Material Sensing and Instrumentation Inc. The uniqueness of this technology is the expanded functionality in comparison to the other cure monitoring methods through the provision of quantitative measurement on the degree of cure at any specific time which includes the later cure phase.

The TDR system uses relatively small electrodes with a control based on the frequency tuning of microwave bands within the range of 10 MHz to 10 GHz. TDR feeds in a rapid voltage pulse which possesses a wide range of frequencies. These frequencies form a dielectric "relaxation response" in rotating dipoles and this response is the degree of cure. A distinct identification is provided from the dipole spectrum which details the cure percent and viscosity. This enables the concentration measurement of unreacted matrix molecules which is expected to go lower even at the end of the cure phase.

3.2.8. *Measurement of cross-linking voltage*

The dielectric and dipole measurement methods measure the matrix response to induce voltages, this alternative method measures the micro-voltage generated from the crosslinking reaction which has been previously neglected. This polymerization induced voltage is small and was in the past assumed to be "electrical noise" and not a measurable parameter. The voltage obviously varies with the progress of cure reaction, the voltage generated from the reaction is apparent and predictable. This allows for the monitoring of all the stages of the cross-linking reaction and establishes the precise end of the reaction. This technique has demonstrated a consistent and repeatable measurement of gel time for various thermoplastics.

3.2.9. *Heat flux monitoring*

This technique utilizes the exothermic reactions from the polymer matrix. The crosslinking reaction also generates thermo-kinetic details that can be used for cure monitoring. This theory is the basis for the heat flux monitoring system, the sensors monitor the magnitude of the thermal energy interaction between the device and the material undergoing curing per the unit time (this is termed

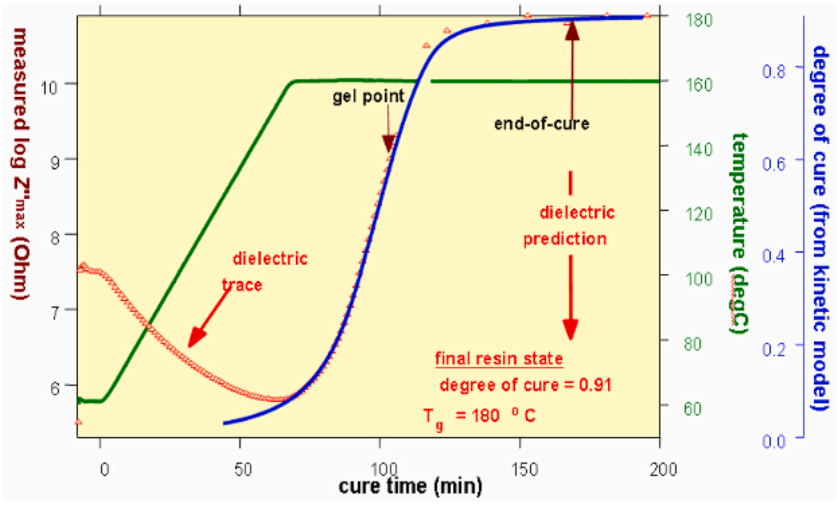


Fig. 13. Dielectric signal evolution (points, left vertical axis), kinematic estimate of cure degree (thick line, right vertical axis) during processing of a typical matrix temperature profile (thin line, right vertical axis) [108].

heat flux). This technology detects and evaluates the flow of both the heat generated from exothermic reactions and the input heat to the device. Subsequently, the cure endpoint can be established.

The beneficial feature of this technology is the unneeded direct contact with the matrix. The sensors can be placed underneath the surface of the device. They detect matrix flow for inflow applications due to the corresponding relationship of the local temperature with shearing and viscosity while the device is filled. The sensors detect the heat generated from the reaction during the cure process and at the conclusion of cure, the sensors detect the thermal exchange stabilization. It automatically ends the cure cycle through varying means such as signalling the consolidating device to open. Industrially, this has been used in several cross-sections of composite manufacturing techniques which include compression moulding, resin transfer mould (RTM), autoclave processing and pultrusion applications. The ability of the system to precisely identify the end of the cure cycle can lead to the reduction in autoclave and processing time.

Pantelelis et al. [107,108] developed an electrical and dielectric monitoring system for real time sensing of the manufacturing process of thermoplastic composite materials. Additionally, the design and manufacture of optimally sustainable non-intrusive interdigitated dielectric sensors was carried out for sensing of the matrix flow, variation in viscosity as well as the material transition and crystallization.

The electrical sensors receive DC signals while dielectric sensors receive an adequate AC stimulus and the feedback is obtained, recorded, and processed by the system proffering real time data on the state of the material (degree of solidification, viscosity, etc.). Using the dielectric setup for room and high temperature processed matrix for regular applications has proven to be robust and capable of detecting the major consolidation stages such as the flow front, minimum viscosity, gel point and end of cure or cooling for the matrix as seen in Fig. 13 below.

The sensors and monitoring systems were successfully used for the monitoring of glass fibre infusion to cyclic butylene terephthalate (CBT) oligomers and this reaction yielded polybutylene terephthalate (PBT) as the final part. This indicates that the designed sensors are non-intrusive, durable, and robust which provides a dependable rationale for real time control as well as provides significant detail on the processing state. Additionally, the electrical sensing system proffers similar real time details as the dielectric sensing system but has a simpler system set-up. It was recommended that the processed data should be combined with a process simulation software for the model-based control generated in parallel which provides an intelligent or smart method of automated and optimized manufacturing process for composites.

The crystallization phase has previously been discussed as a vital aspect of the solidification process for thermoplastic matrix, Hübner et al. [109] used online in-process monitoring of the crystallization process with the aim of enhancing the part production and subsequently advance the application of this field. Although methods such as scanning electron microscopy or differential scanning calorimetry can be applicable here, they are insufficient for online monitoring. Another challenge in sensor selection was the large size which could not be used as it hampers the mechanical integrity. Hence, a miniaturized interdigital dielectric sensor was used for crystallization process monitoring of polypropylene at two varying cooling rates. The generated amplitude of the impedance was measured where the position of the peak of permittivity was related to the crystallization. Additionally, the difference in impedance observed for both cooling rates indicated that there is a tendency for a material to have differences in crystallization processes. This sensor was recommended due to its potential in monitoring the crystallization process and establishing the exact time crystallization occurs for various production processes. Also, due to the miniaturized size of the sensors, it can be applicable in composite parts with complex geometry. Sernek and Kamke [110] conducted a continuous in-process consolidation monitoring of phenol formaldehyde (PF) adhesive through dielectric analysis. The study also examined the effect of wood moisture content on the dielectric signal from the PF adhesive bond. It was observed that the dielectric changes corresponded with PF adhesive curing in the bonded region. Additionally, the change in moisture content did not significantly have an effect on the obtained dielectric signal from the adhesion process.

Balvers et al. [111] embedded dielectric sensors to monitor the curing of resin transfer moulded (RTM) thick composite panels. Fabricating thick samples can be traditionally associated with processing challenges because of the exothermic reaction occurring within the matrix system. The rationale for using dielectric sensors was based on measuring the influence of the exothermic reaction on through-thickness evolution of the curing phase. Also, DSC tests were incorporated into the dielectric ion measurements to correlate the result of the tool mounted and embedded dielectric sensors to the cure phase of the high performing manufacturing in-situ during manufacturing. Additionally, models are generated for cure kinetics and glass transition temperature with the chief intention of optimizing the cure cycle for thick materials as well as predicting the through-thickness glass transition temperature and degree of solidification. Although some differences were noticed between sensors embedded in the mould surface and the middle of the laminate due to the exothermic reaction increasing the temperature in the middle of the laminate, a correlation between the log ion conductivity, glass transition temperature and the degree of curing was not achieved. Therefore, it was suggested that more experimental studies are vital for a thorough understanding of the curing phase in thick-walled composite materials and the improvement of techniques for manufacturing varying thicknesses. Additionally, the thickness of composite materials should be considered during the simulation modelling of the curing phase.

3.2.10. Fibre optics

An approach that is currently in development for direct cure monitoring is the incorporation of fibre optic sensors. They are currently the subject of extensive research and developmental attempts for several composite monitoring applications. Using these smart means can provide direct feedback for several purposes such as intelligent control, structural health monitoring, improvement of structural design, design analysis, strain sensing and damage detection. Their distinct small size enhances the tendency of embedding the sensors in the composite part whilst retaining the integrity of their mechanical properties [5].

Generally, strain measurements of a material using the optical fibre Bragg grating (FBG) technique is the most advanced optical

cure monitoring techniques. This is mainly as a result of the surge in the adoption of structural health monitoring where FBG is mostly used for in-service monitoring of the structures. Presently, the use of strain measurement for cure progress monitoring has not been thoroughly investigated although there is improved study into process induced residual strains. This technique utilizes embedded optical fibres in the matrix that monitors the strain accumulation within the material which is generated from chemical shrinkage and restricted thermal deformation during cure.

Basically, optical fibre are waveguides used to contain light rays. They are primarily comprised of silica glass cores coated with a cladding of lower refractive index. Subsequently at the boundary, total internal reflection occurs which propagates light across the fibre core. A basic structure is displayed in Fig. 14a. Extra polymer layers are also added to proffer damage protection (encapsulation).

The FBG sensor is a type of optical fibre that has a longitudinal periodic modulation in the core refractive index that serves as a filter for the narrowband reflection [112]. These sensors are usually 3–15 mm long. The mode of operation for measurement in wavelength variation of the reflected signal specifically for Bragg wavelength that is illuminated with a broadband source of light. This illustration is displayed in Fig. 14b.

The Bragg wavelength relies on the grating periodic spacing (Λ) and the effective refractive index of the core (n_{eff}).

3.2.10.1. Theory. The Bragg wavelength (λB) can be stated as (16):

$$\lambda B = 2\ \text{neff}\ \Lambda \qquad \text{(Eqn 3.7)}$$

As a result, any exterior factors such as temperature (ΔT) and mechanical strain (Δε) which can easily influence the grating properties can also create a reflected wavelength shift.

For an unattached fibre, the wavelength can be expressed as:

$$\Delta\lambda B = \lambda B\ (K\ \Delta\varepsilon + \beta\ \Delta T) \qquad \text{(Eqn 3.8)}$$

Where β represents the wavelength to temperature sensitive factor (approximately 10 p.m. or °C) and K is the wavelength to strain sensitive factor (approximately 1 p.m. or macro strain). Therefore, the effect of temperature is about 10 times more substantial than the influence of strain which makes temperature compensation vital for precise strain deduction. The factors can be further resolved into:

$$K = 1 - pe \qquad \text{(Eqn 3.9)}$$

$$\beta = \alpha\Lambda + \zeta \qquad \text{(Eqn 3.10)}$$

Where pe is termed the effective strain to optic constant and 1 – pe represents the gauge factor of the grating while ζ stands for the thermo-optic coefficient and αΛ represents the thermal expansion coefficient. In plain terms, these factors can be modified to be responsible for the following:

- Thermo-optic coefficient (ζ) - the influence of both the temperature and thermal strain on the refractive index.
- Strain-optic constant (pe) – influence of mechanical strain on the reflective index.
- Thermal expansion coefficient, αΛ-influence of thermally induced strain during grating.

Hence the measurement of Bragg wavelength variations induces linear effects of the forced strain which emanates from both thermal and mechanical expansion as well as the influence of non-linear properties of refractive index.

Restricted fibres especially fibres embedded in a material act as free fibre but with more contribution from the thermal expansion of the enclosed material. Thus, the 'restricted fibre' can be expressed as:

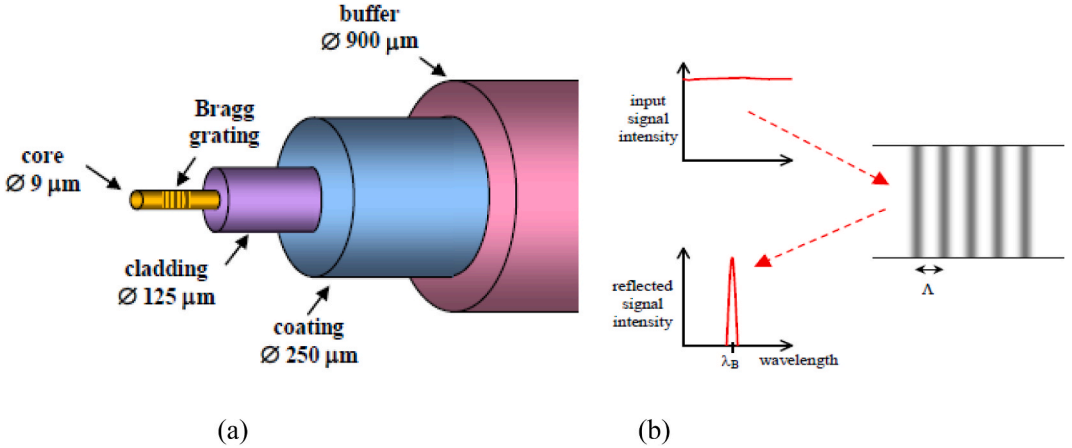


Fig. 14. (a) Basic illustration of the fibre Bragg grating (FBG) optical fibre and (b) classic spectral response of FBG sensors [70].

$$\Delta\lambda B = \lambda B\ (K\ \Delta\ \varepsilon + \beta\ \Delta T + K\ (\alpha s - \alpha\Lambda)\ \Delta T) \quad \text{(Eqn 3.11)}$$

With αs representing the thermal expansion coefficient of the host material or substrate layer.

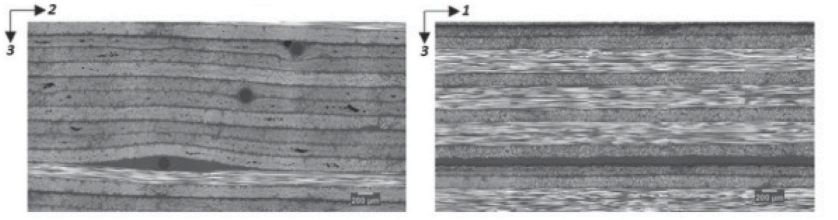
The most prevalent procedure for installing optical sensing fibres on a part is to mount them directly to the surface. Proven methods and materials are reliable and can be applied in the surface-bonding of the sensors onto the part. Also, optical fibres tend to integrate well inside composite structures with interesting advantages and the potential of being used in novel applications. Applications of optical fibre sensors such as FBG sensors provide benefits that they can be utilized to create the basis of more complex transducers, which provide the measurement of other electrical, environmental, chemical and physical variables. Examples of applications with such sensors include the detection of defects, salinity measurement, strain, humidity, temperature and the analysis of vibration, fluid flow and pressure.

For cure monitoring, fibre optic sensors can be networked or set up to emit infrared (IR) signals through a small area of the matrix in the layup and the energy is absorbed which is subsequently released by the chemical components of the matrix and this enables the capturing of spectral data. As chemical bonds display unique vibrational frequencies in IR energy absorption and release, the obtained data can be evaluated to quantitively ascertain the crosslinking degree. Although optical fibres are presently common instruments, an analytical device that interprets the signals that are carried by the fibre is relatively costly for general applications. However, it is expected that fibre optic cure monitoring will be boosted with increasing knowledge on structural health monitoring and this is due to the ability of the same fibre to serve in both capacities [5]. Challenges of this method are the massive shear–lag effect due to coating, cladding and adhesion of layers covering the optical core which makes them difficult for taking precise measurements and additionally, the fibres introduce weak areas in the laminate as potentials for delamination and crack sites [113]. However, optical fibres are broadly used for large structures as they can be easily multiplexed over lengthy distances [114]. With embedded FBG sensors, the residual strains acting on the FBGs can be measured during composite manufacturing. Research in this area indicates there is a dual potential for (small diameter) optical fibres as FBGs can measure strains, as well as cracks.

Several studies have used FBG to monitor the strain and temperature of thermosetting composites in the consolidation phase [115–118]. However few studies have monitored thermoplastic composites [119–121] specifically for in-situ consolidation processes based on automated manufacturing [73,75]. Tsai et al. [122], embedded a distributed optical sensing (DOS) monitoring system for in-situ strain measurement. Optical Frequency Domain Reflectometry (OFDR) was used rather than Optical Time Domain Reflectometry (OTDR) due to better spatial resolution deployed to detect and acquire optical data for the DOS for more precise and efficient measurement of strain and temperature. This provides the DOS with beneficial features such as simpler composite structure embedment, great measurement sensitivity, simultaneous strain measurement across the whole sensor length, great spatial resolution and low-cost (sensors made from commercial glass fibre). It was observed that resin pockets are developed around the sensors and the location of the sensor relative to the interface and the geometry of this pocket relied on the local stacking sequence of the laminate (see Fig. 15 (a, b)).

The thermal history and strain evolution was then analysed at 7 key stages where the glass transition temperature, temperature-time history and degree of cure are influential factors. Although this study gives a good validation, the mode of sample manufacturing herein which is a vacuum bag differs from the automated technique and it is expected that the results will differ when subject to in-situ heated consolidation and varying heat sources [67].

Woerdeman et al. [123] developed a cure monitoring sensor that was based on the evanescent wave fluorescence measurement which was carried out through optical fibre embedded in the prepreg. A wavelength-shift probe was the selected fluorescent dye for in-mould cure monitoring and this wavelength shift was monitored during liquid moulding. The wavelength maximum of the fluorescent which occurs during cure decreases with the matrix conversion as ascertained by infrared spectroscopy. Furthermore, the level of matrix conversion was established from the calibration curves. The evanescent wave fluorescence sensors also indicated the capability of identifying issues such as matrix degradation. The addition of lead oxide increases the refractive index of optical fibre above that of the matrix which enables evanescent wave sensing. Evanescent wave sensors facilitate measurement at $\sim 1\ \mu m$ radius of the fibre surface and this provides the measurement of the matrix cure that is the most applicable in predicting the properties of the end part. Also, the incorporation of arrayed cameras and imaging spectrograph to increase data acquisition aided the evanescent wave



(a) From the top to the bottom: sensor embedded between [0°/45°], [0°/0°], and [90°/45°]

(b) A continuous resin pocket forms between the interface of [90°/45°]

Fig. 15. The microscopy highlights (a) the resin pocket formed from the embedded sensor (b) the layer interface for the continuous resin pocket [122].

fluorescence sensor to be applied as cure controller and can also lead to a significant improvement of time resolution.

Kim et al. [124] worked on the cure monitoring of carbon fibre-reinforced epoxy composite materials to ascertain the dissipation factor which serves as the cooling initiation point and thermal residual stress through dielectrometric and FBG sensors simultaneously. A three-point bending test was done to investigate the influence of cure cycles on the residual stress. Thermocouple was also embedded to compensate for thermally induced shift in wavelength and placed close to the FBG sensors for local temperature measurement (displayed in Fig. 16 (a, b)). The critical points were estimated based on the derived dissipation factor and this was used to control the precise bond temperature at the interface between fibre and matrix. A significant decrease in thermal residual strain and an increase in flexural strength was achieved.

Chen et al. [125] also used an encapsulated FBG for process monitoring of woven fabric thermoplastic composites and thermocouples as reference with the average measured difference between them being 2.92 °C. Also changes in residual stresses of the composite were displayed by the micro bending which created an optical power loss of the fibre pigtail that is initiated at the glass transition temperature during the solidification phase and this can be oppositely used to signify the formation of residual stresses in accordance with the decrease in reflectivity of the FBG spectrum. Also, the embedment of the sensor head did not induce significant initial defects in the created composites due to their small size. Furthermore, the study explored the stress and temperature variations of the composite during the forming process which supports the possibility of in-situ monitoring through embedding sensors in harsh conditions. This subsequently enables the establishment of a relationship between the actual temperature and the set temperature during the forming process. Therefore, the normalcy in the reflectivity and residual stresses changes. The encapsulated FBG can also be multipliable as both the ingress and egress lines can be fabricated by bonding the capillary to both ends of a slightly bent FBG. Hence, multiple sensors can be used to form a network which measures temperature at several points in the composite.

Tsukada et al. [115] addressed the produced-induced residual stress or strain distribution from thick thermoplastic laminates because of the non-uniform temperature distribution. The residual strain and stress in carbon fibre reinforced poly phenylene sulphide laminates through FBG sensors to determine the stiffness and thermal or crystalline shrinkage. Fig. 17 graphically illustrates the strain across the embedded optical fibre. The distance of the FBG to the fibre edge is termed "tail length". The shrinkage strain of the composite ϵ_{host} is conveyed to the embedded optical fibre mostly through the interfacial shear stress moving to the end of the optical

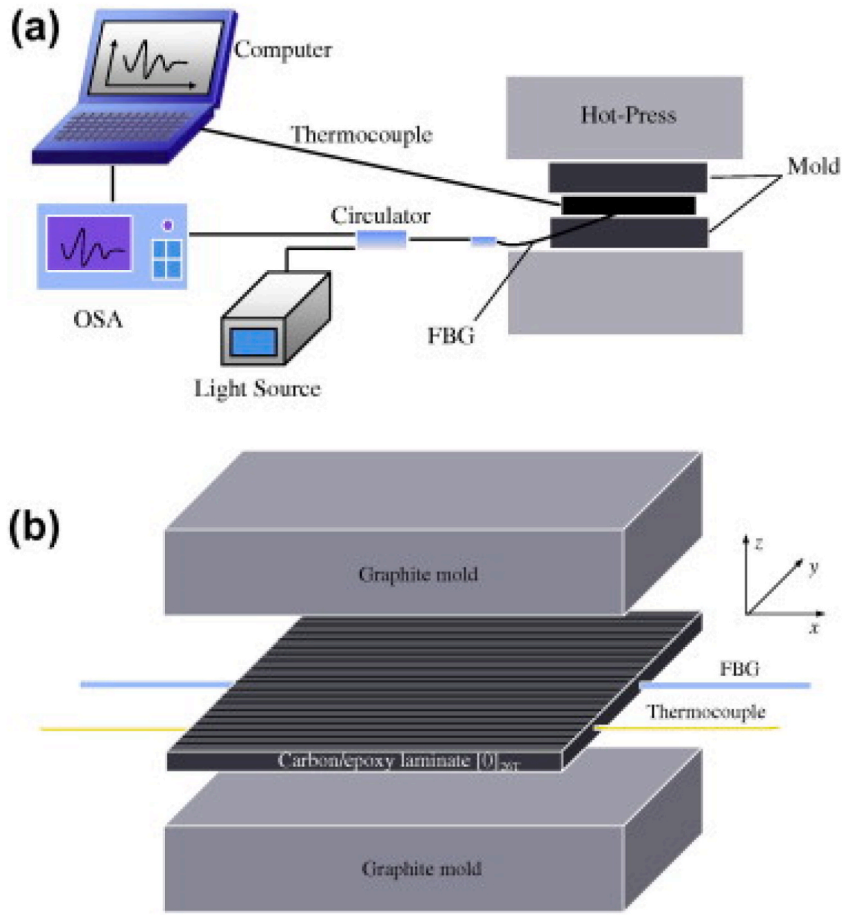


Fig. 16. Internal strain measurement of composite laminates: (a) illustration of the experimental setup, (b) FBG sensor embedment into the composite laminate [124].

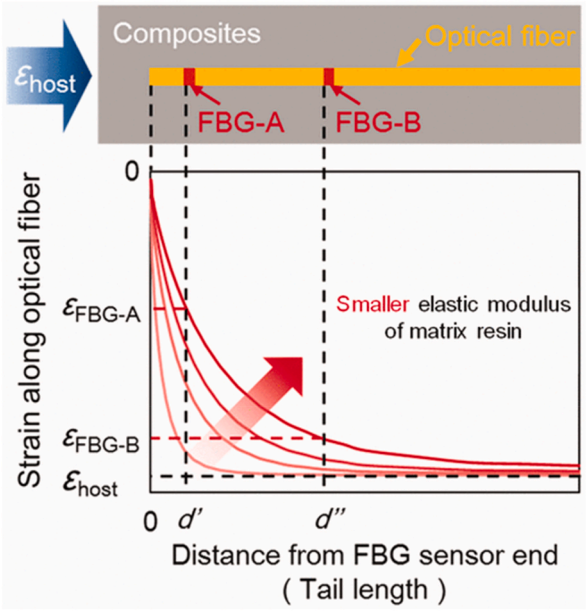


Fig. 17. The effect of elastic modulus of matrix and tail length of FBG on strain measurement via embedded FBG sensor [115].

fibre.

Through this investigation, process monitoring facilitates in clarifying the internal state of change of the composite during solidification. For automated composite manufacturing in comparison to other methods, the ability of the machine to produce customized parts enlarges the application range of this manufacturing technique. To enhance the quality of thermoplastic composite parts through this manufacturing technique, a dependable technique is vital for monitoring the manufacturing process. However, Tsouvalis et al. [126] expressed that based on the high processing temperature of thermoplastic composites, basic strain measuring methods such as strain gauges are not trustworthy as measuring results. Furthermore, where the laminate is embedded with strain gauge in the form of a foreign body, the structural integrity of the laminate can be altered.

Based on the knowledge that real time monitoring during the layup manufacturing process of the laminated composite is a feasible method that can be incorporated into real time automated manufacturing of advanced composites [13], Oromiehie et al. [74] attempted to present that silica optical FBG sensors can be used in identifying two most common type of misalignment defects (overlaps and gas) in the laminated composites as well as foreign debris presence detection if any lies within the plies during the AFP process. The experimental configuration for the on-line monitoring of the lay-up process is displayed in Fig. 4a above. For this study, the identified defect was artificially induced and the FBG response in this experiment was pressure and temperature induced strain. For understanding the process parameters (pressure and heat) individually, a different FBG sensing network is necessary. This was achieved through using twisted or angled FBG that eliminates the cross sensitivity of temperature and strain in the lay-up process. The obtained results indicated that based on the defect type which includes the material and size, significant changes in the wavelength profile are noticed and reveal that the reflected wavelength changes enable the identification of the defects. Further work on embedded FBG for realistic in-situ process monitoring was encouraged.

Parlevliet et al. [127] used FBG sensors as an experimental device to ascertain variations in the residual (thermal) strain levels across the thickness of a thick glass fibre reinforced polymer laminate. The obtained residual strain was possibly initiated mostly from thermal shrinkage of the laminate during cooling down in service temperature from the different peak temperatures. FBG also indicated potential in monitoring flow behaviour within a thick laminate, it clearly presented the pressure differences from the movement of the flow front. In subsequent research, with solidification shrinkage of the matrix being the major source for residual strain

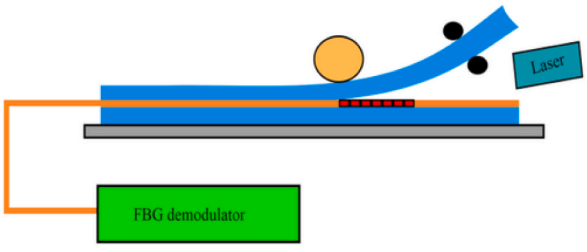


Fig. 18. Operational illustration of the FBG sensing embedment during AFP [129].

development in thick composite laminates, Parlevliet [128] investigated the impact of this and post solidification to the residual strain formation using FBG. The results from FBG for thermal transitions and expansion of the solidified polymer corresponded well with results derived from DSC and dilatometry (TMA) results and this indicates that FBG sensors can provide reliable data.

Zhan et al. [129] discussed the FBG sensing principle and the major techniques as well as prioritizing the wavelength demodulation. It was deduced that high speed optic fibre grating demodulation technology is mainly applied to optic fibre grating sensing in the thermoplastic composite field. This enables an accurate and rapid measurement of the identified parameters which in this case were the temperature and strain. It was also discovered that this technology has an increasingly vital role in monitoring the automated thermoplastic composite manufacturing process. Hence, a high speed FBG demodulator was used to extract information from the central wavelengths of the FBG at varying laying directions and AFP was the manufacturing technique used (Fig. 18). Laying the sensors at varying directions enables the collation of strains and temperature by matrix calculations as strain sensitivity coefficients vary. Polyimide fibre grating offered in addition to FBG advantages, a smaller diameter.

The FBG sensing system was discovered to be suitable to measure the strain and temperature during in-situ consolidation of the composite. A reference for optimizing the consolidation process is provided from the measured strain of the composite during consolidation. The precision of the strain and temperature measurement system was noticed to be 1 με and 0.1 °C respectively which accurately reveals the internal condition of the material with no defect formation in the material. These results were subsequently validated and corrected through strain gauges and thermocouples.

Saenz-Castillo et al. [120] investigated the use of FBG for process monitoring during thermoplastic composite consolidation through embedment. Additionally, thermal history was simulated to create a thermal model, and this proved successful as the sensors enabled the identification of the various processing phase (heating, consolidation and cooling down or curing). Herein the thermal history or distribution was monitored by enclosed FBG sensors serving as temperature probes. A good relationship between the thermal distribution and sensors was noticed and this was also attempted for strain distribution. This was the similar conclusion to the work by Del Castillo et al. [75] where the change in temperature measurements between the thermocouple and FBG was resolved through modifying the encapsulated sensor which was a basic FBG. FBG was also expressed to be a good method of visualizing the influence of the residual stresses created from manufacturing as this is noticed in wavelength shifts. It was recommended that FBG should be used in investigating the real time monitoring of the influence of the manufacturing or process induced defects during consolidation.

However, the embedment of optical fibres during the manufacturing process involves the method of directly integrating the optical fibre with sensors into the laminate during the manufacturing phase [130]. The susceptibility to failure, sensor position and difficulty in handling the optical fibres during manufacturing renders the technique non-practicable for (automated) manufacturing processes. Furthermore, optical fibres are more prone to fail at the ingress and egress areas if the fibre is emerging from the edge of the composite or protruding through the surface. Any optical fibre reinforcement should be made at the ingress or egress regions, and usually heat shrink or Polytetrafluoroethylene (PTFE) tubing, or silicone impregnated thermoplastic braids can be used here. It is imperative that the edge of the (embedded) tube is covered to prevent the matrix from flowing down the tube. The presence of any additional matrix which coats the fibre can make it extremely prone to damage. Fibres that come out from the edge of a laminate can be easily embedded because the fibre can be placed between plies. However, the laminate edge cannot be trimmed after manufacturing as it is often impossible and unacceptable for composite structures. Also, the appearance of the fibre on the surface (away from the edges) is more complex to attain as the fibre must be pulled through numerous plies. Usually, various plies are cut with this method, and precautions is necessary to avert the excessive bending of the optical fibre. It is essential that the fibre comes out at a shallow angle across the material and to be supported by wedges on the surface. Additionally, a procedure for extracting and replacement of these sensors should be considered. For a more robust approach to accessing an embedded optical fibre, a connector can be used to house the embedded sensor on the surface of the composite and serves as a connection location after the completion of the consolidation process.

The drawbacks with NDE or NDT monitoring of pipes such as TCP are the availability of specific device size impedes the possibility of testing smaller pipes while the bending radius can also limit the ability to use certain devices [131]. Also, frequent non-destructive inspections (NDI) of parts proffers insight into their performance but the complications of these techniques usually cause significant downtime and increased labour costs. An example of the cost implications for inspecting these composites is that it can represent up to a third of the lifecycle costs [132]. Moreover, current methods used industrially to monitor the structural integrity of pipelines are not 100% precise, therefore, the development of a highly reliable and cost-efficient monitoring system would provide several benefits for pipeline operators.

4. Challenges, recommendations, outlook and concluding remarks

4.1. Advanced materials

With the ever-increasing frontiers involved with energy production, various advanced materials which include polymer-based composites are always evolving and garnering appeal. This can be attributed to several benefits which include high strength and stiffness to weight ratio. Also, using flexible pipes especially TCP as an alternative to metal-based rigid pipes for flowlines has been presented as a cheaper solution. They have higher strength and stiffness to weight ratios in comparison to conventional metal-based pipes. The greater the specific properties (stiffness and stress) of the composites, the greater the operational range and payload capacity and also an improvement in the mechanical performance of the pipes. TCP is a high performing composite pressurized vessel designed to perform better than RTP in remote and harsh locations based on the solid wall construction with the one material concept. This wall consists of 3 layers which are the liner, laminate and coating with all these 3 parts having the same polymer material (one material). As a result, the performance of the TCP can be traced down to the fibre, thermoplastic matrix and the interface between them, using

thermoplastic materials assists in providing a high allowable strain and as a result makes TCP flexible and spoolable. Understanding the material constituents will assist in determining the best manufacturing techniques.

TCP which is a fibre reinforced polymer composite pipe is a combination of low density and great mechanical performance which makes it ideal for high performance applications. Fibres employ the greatest possible reinforcing influence when they are non-crimped, uniformly distributed, continuous, and aligned to the loading direction while the matrix should offer compatibility. Prior to utilizing TCP like other fibre reinforced polymers, understanding the significant material properties is vital as well as the availability of appropriate manufacturing technology [133,134]. The conventional methods for producing composite structures are limited due to two key factors which are firstly, the hand layup process, which is laborious and time consuming and secondly, composites (mostly thermosets) require a long post processing time using the autoclave curing cycles. These factors can be resolved through the incorporation of automated methods with no challenges of reproducibility and the use of thermoplastics as an alternative to thermosets respectively. The melt fusion bonding technique through automated processes is the current traditional manufacturing procedure for TCP due to the several advantages thermoplastics offer. This technique requires the application of pressure and heat at the interface which has the potential on fast in-situ processing without the necessity of curing in autoclaves. Attention on the development of thermoplastic composites is encouraged through the high impact, chemical and solvent resistance, improved damage tolerance, recyclability, and weldability. In addition, the combination of the automated processes and fusion bonding enables in-situ bonding as the process is quick, clean as well as done out-of-autoclave (OOA). However, this can pose a challenge for thermoplastics as they have a high viscosity. Furthermore, there is a huge possibility that defects are induced into the structure during manufacturing (cure phase) and some of these key defects and phenomena are voids and residual stress. Also, other parameters influence manufacturing defects such as the melt temperature, consolidation pressure, layup rate etc. When manufacturing defects is not monitored and fixed on time, through certain mechanisms in-service defects is bound to occur and this includes delamination and fibre pullout.

4.2. Manufacturing process

For the manufacturing process, the feed tape or tow and substrate are initially irradiated by the heat source and are then compacted at the nip point in accordance with in-situ consolidation. For thermoplastics, the heating rate is prevalently determined by the level of irradiated regions on the tape, light reflection at surface, degree of heat absorption and optical properties of the material. The nip point temperature which can be termed the processing temperature is modulated for consolidation quality control and final mechanical properties of the composite part. For fibre-based materials, the relationship of the heat and embedded fibres is also vital. For the matrix material which envelopes the fibre, they should be relatively thin to enable a substantial absorption of heat that reaches the fibre surface and optimizes the fibre-matrix interaction at their interface [135].

Noteworthy, most of the work for monitoring composites during manufacturing has focused on thermosets. This is because thermoplastics are significantly viscous and stiff which is highly unfavourable at high processing temperature and pressure conditions that consequently increase the manufacturing cost. This contributes to the formation of the stickiness of laminates (tack) and draping of the matrix which is formed during the automated melt fusion bonding is another factor that is presently considered to influence the end quality of the produced part. Furthermore, the entire heating-cooling process for thermoplastics occurs within a relatively short time (~10s) on a small and moving region where the applied pressure (consolidation) is only for a short period which is lower than an autoclave, it makes it difficult to derive parts that are at par with autoclave-scaled materials. The automated process is also deficient in producing geometrically complex or curved parts such as TCP with specific load that subsequently affects the part economically. Increased consolidation speed indicates reduced times and increased challenges. Hence, it can be understood that despite the possible benefits of using this manufacturing technique, the adoption of this technique for mass serial production is constantly evolving research [133,136,137].

Also, the manufacturing process has multivariable activities that involve several procedures that encourage the formation of defects (e.g., voids, fibre misalignment, delamination and residual stress) within the composite product which consequently raises safety concerns in service [138]. The presence of defects can result in a substantial loss of performance for the produced part. Therefore, prior to applying the material in any field, understanding the significant material properties is vital as well as the availability of appropriate manufacturing technology [139]. Furthermore, with the increasing application of composite in environmentally demanding and high-performance conditions, thorough characterization at every stage is needed to determine the formation and propagation of failure. Therefore, while this review has provided insight into the current characterization techniques and methods of understanding the material properties which is applicable to TCP, further work will be required to refine these methods and explore innovative techniques for quantifying the identified defects in an in-situ approach. Detecting and assessing these defects for structural integrity monitoring is peculiarly challenging as composites are anisotropic and non-homogenous. These defects and failures can happen at several locations and at varying scales which renders it difficult in monitoring all the affected regions that can cause complex failure modes. Furthermore, accumulated failure within the composite can be linked to the actual stiffness, strength, and lifespan prediction of the part. Hence, a reliable and robust testing method is salient for minimizing the safety concerns and cost of maintenance to reduce the possibilities for downtime and processing stoppages. This makes this field appealing for both academia and industrial research. Practically, the appropriate characterization technique is to be selected based on the samples, the requirements, and the potentials. It will also be important to know if the defect amount is within operational threshold for TCP or if an elaborate 2D or 3D analysis of the morphology, distribution and size is necessary. It is also imperative for TCP manufacturing that the characterization technique is non-destructive, in a continuous order and provides on-line monitoring [140].

To ensure the quality of the finished part and to enable the optimization of the processing parameters, a thorough assessment of the manufacturing process is greatly desired. An instance is, during impregnation, it will be crucial that the adhesion process of the matrix

and fibre be controlled or else there will be gap formation between fibres owing to poor resin distribution and will consequently have an adverse effect on the resistance and mechanical property of the part at in-service conditions. Overtime, several methods have been proffered for the monitoring of composite manufacturing such as the ultrasonic technique, thermocouple sensing, dynamic mechanical analysis (DMA) and differential scanning calorimetry (DSC). However, they are mostly either appropriate for lab scale conditions or limited to specific cases. An instance, thermocouples can be used in detecting that when a mould is filled as there is a significant temperature gradient between the mould walls and feed resin or be used in enabling the prediction of cure onset through measuring the exothermal behaviour as low heat dissipation can create massive temperature gradients within a laminate.

As stated in this review, DSC is broadly utilized in characterizing the cure kinetics and provides details on the glass transition temperature (Tg), cure onset, cure degree and rate of cure. However, the DSC technique is limited to minuscule scale samples (~6–10 mg) and hence is not suitable for composite manufacturing. Furthermore, amongst the other discussed techniques, the ultrasonic technique requires 2 transducers which are placed at opposing distances that make it vital in deriving the precise measurement and an extra distance control device is often needed. Using this technique will be limited to more advanced composite material or manufacturing processes [141].

From this review, FBG sensors have proven to precisely determine the during and post process induced residual strains as well as the thermal expansion behaviour of a fibre reinforced polymer [118]. In a similar way, a flexible dielectric sensing system can be used for monitoring the production of composites. The derived data obviously indicated the various vital phases of the production process (e.g., flow front, matrix (de)vitrification, cure progress and ending of cure). The sensor also displayed higher sensitivity in comparison to thermocouples. However, this result pertains to thermosets as their behaviour in heating and compacting condition was not considered [141].

4.3. Relationship between manufacturing induced defects, the processing parameters and detection techniques

Additionally, it is imperative that the relationship is firmly established between the behavioural features of the manufacturing induced defects and the processing parameters, as well as the link between the defects formed at the consolidation phase and the final defect form after consolidation which will be beneficial for enhancing the mechanical properties of the part [13]. This is vital as a precise nip point temperature control will need quantitative models to identify the angle, light reflection and material dependent absorption [142]. Therefore, considering this review, an online monitoring approach is required to not solely establish this relationship but to avoid time wastage from interval visual inspections. Schmidt et al. [143] integrated a thermal in-situ monitoring system into the manufacturing process to address this challenge. The detection of defects and localization of the tapes was made possible by the temperature differences of the substrate and tapes. This temperature difference is dependent on the processing parameters such as machine temperature, compaction pressure and speed. Through this study, a process parameter-based determination of the thermal threshold values was achieved. This facilitated the detection of temperature differences from lower temperature deviations and assisted in analyzing the defect features. Also, the process parameters proved to affect the laminate quality as the ply positions in the laminates can vary from the first ply due to the parameters. For thicker laminates, these parameters can be used at a set value. Hence, it is salient to establish the influence that the processing parameters such as material temperature possess. For thicker laminates, a hypothesis was made that for all compaction pressures greater than the minimum required compaction pressure and the combination of the mean temperatures for varying compaction speeds does not affect the temperature distribution. However, any thermal model to be used in predicting the thermal distribution for some processing parameters should be based on an efficient thermal on-line monitoring system.

The use of camera and optical techniques is presently receiving some attention, Zaami et al. [142] developed optical models for predicting the heat absorption and reflection behaviour of fibre reinforced thermoplastic composite during the manufacturing process which was validated through optical characterization. Also, a genioreflectometry was used for elaborate analyses of the anisotropic reflectance behaviour which was linked to the fibre alignment within the laminate. The developed model was able to assist the computational tool by precisely predicting and optimizing the processing parameters for laser assisted composite manufacturing processes. Progress with this technique will involve the incorporation of both statistical description and temperature dependency on the tape reflectance behaviour into the model.

Although methods which involve a camera such as digital image correlation (DIC) provide insight into the damage and deformation of non-uniform strain field and surface displacement during use, they are inherently limited to only the surface as the internal and structure of the material is also crucial for comprehending any fails. The use of the DIC to quantify the mechanical and failure behaviours at the matrix-fibre interface by measuring the strain fields and deformation in the fibre and matrix as well as the around the interface. However, it is recommended that a 3D DIC can be used but in two main forms which are the firstly, the use of two cameras for conventional 3D DIC which will enable the measurement of strain regions and out-of-plane deformation. Secondly, to exploit the transparency of some matrices and developed cameras that are orthogonal to each other and perpendicularly to the side and front of the specimen. This will ensure that while one camera tracks the frontal region of a sample which collates strain data, the second camera will follow the fibre along the transparent sample to observe the internal debonding patterns. This can be significantly useful for characterizing the crack propagation in the fibre direction and the post debond behaviour [144].

Adopting acoustic emission technique has been established as being effective in the determination of failure onset but requires a combination of other techniques to locate these failures. Alternatively, infrared thermography can proffer the locations of failures in the composites by the use of a heat map. However, this is a surface observatory method will be misrepresented due to the anisotropic thermal properties of the fibre reinforced composite. Furthermore, the possibility that defects (damage) formation can be deduced from non-uniform surface displacement and strain fields. Several photogrammetric methods (e.g., elementary speckle interferometry,

holography, Moire interferometry and shearography) have been explored to obtain a more precise outcome through the use of lasers or white light. However, the most renowned non-contact technique for composites during failure is DIC. The digital volume correlation (DVC) improves the details derived from μCT which enables the measurement of strains and internal deformation. DVC which depends on utilizing the voxel sub volumes to ascertain the strain and internal deformation which seems promising with fibre reinforced polymer composites. However, this technique is limited to materials with ample internal phase variation and X-ray variation.Ultrasonic testing is still the best tool used industrially for assessing defects and accepting or declining decisions, as well as the best industry standard procedures. However, the ultrasonic inspection does not give precise information on defect morphology, spatial distribution and individual size. Although it is expensive, the micro-CT is the most reliable, advanced, detailed (visualized) and precise method for analysing defects. The quantification approach using micro-CT is ever evolving and is still very much an active research area for the foreseeable future. The key limitation of the high-fidelity micro-CT is that samples are of minuscule size [144].

Presently, the on-line monitoring methods for manufacturing defects is projected to apply thermographic monitoring, digital image processing, machine vision, dielectric and optical sensors etc due to their suitability in being applied in real time and in-situ. However, the transferability from laboratory to industrial scale remains in progress as the sensing system must closely retain its sensitivity and reliability, while also being produced at cost efficient and simple methods. Also, these methods (thermographic monitoring, digital image processing and machine vision) can only detect defects at the surface for thermoplastics which necessitates that each ply be monitored during manufacturing, but these will generate a large volume of data while the detection of internal defect evolution which will be inaccurate. Hence, the monitoring of internal defects for each manufacturing phase through physical waves and optical sensors is feasible. Although the optical FBG sensors have been extensively studied as seen earlier, they must be embedded in the melt phase of the laminate. This presents an issue as the sensor should be removed and then the material cools. Online ultrasonic and stress wave detection are quite recent approaches to monitoring internal stress distribution. However, the specificity of the defects may not be spotted. In addition, the defect behaviour and processing parameters is yet to be fully understood as stated earlier and if done, will assist in deriving a practicable process-based control approach. This implies that there is potential in combining the different sensors based on their beneficial features to produce a multi sensor online defect mechanism which is then applied with the process control approach to be an area of focus to consider for in-situ characterization and control of defects in the long run [13]. Holmes et al. [144] have combined DIC and μCT with DVC for characterizing damages and deformation. The DVC proved capable of identifying regions with great out-of-plane strain which can be correlated to the delamination and cracking onset. Similarly, Kousiatza et al. [116] integrated FBG and thermocouples sensors into carbon and glass continuous fibre reinforced thermoplastic composites of varying fibre orientations to decipher the real time residual strain formation and the generation of temperature profiles during the manufacturing process. The FBG sensors were also used to identify the magnitude of the in- and post-fabrication induced strain and analyzing the composite material behaviour to thermal loading through a thermal cycling test. It was deduced that the fibre type and orientation significantly affect the process induced temperature residual strains and temperature profiles as well as the derived CTE values that is specific to the sample. The FBG sensor was able to demonstrate its potential in precisely determining the thermal expansion response of the composite and the in- and post-process induced strains.

4.4. Quality control and manufacturing data processing

On a holistic scale, the described testing methods are based on varying principles and have been proven to be efficient in terms of quality assurance for the entire lifespan of the part (e.g. processing control, processing optimization, monitoring the manufacturing, in-service monitoring and structural health monitoring). Therefore, asides from considering the manufacturing defect formation, their influence on failure mechanisms and obtaining the mechanical and physical properties of the material, to maximize the use of the in-situ consolidation technique, other factors such as process optimization and quality assurance should be considered [145].

For process optimization in these novel materials, the processing window is determined through trial-and-error methods. Herein, process modelling can be utilized in decreasing this iteration technique and optimizing the process by evaluating the effects of processing variables on the manufactured part. Several microstructural changes also influence the properties of the part such as melting,

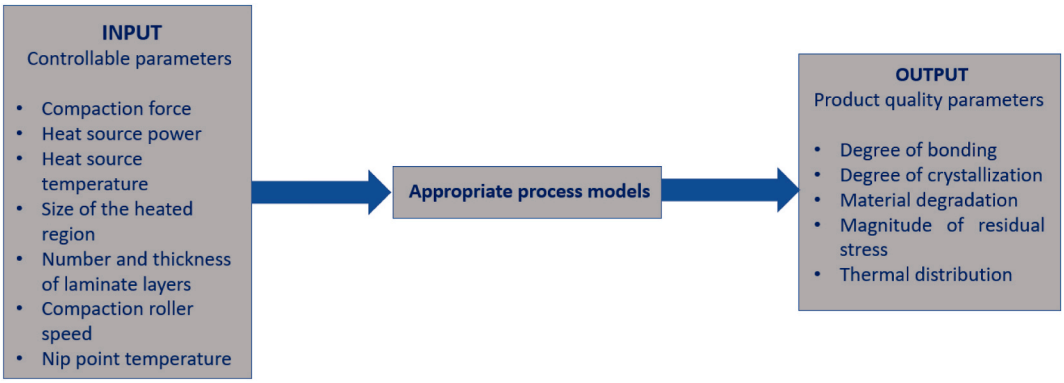


Fig. 19. The optimization process displaying the outputs and inputs of an automated processing model.

crystallization, degradation, intimate contact, autohesion, interconnection of voids and propagation as well as residual strains. The selection of the appropriate process parameters significantly influences any microstructural changes which subsequently influence the final mechanical properties. The windows of processability are generated dependent on the specific quality requirements for proffering the threshold for the allowable values of controllable process variables (the applicable processing model is displayed in Fig. 19).

Also, the processing window can be used to discern the optimal parameters set values which will enable the in-situ consolidating thermoplastic composite process to compete with that of thermoset with regards to the minimization of processing time and maximizing the bond strength. The processability window which is greatly temperature dependent, has a narrow range between the upper boundary which going beyond it can be characterized as degraded material as a result of excessive temperature, lower boundary whereby if it goes further down will be characterized as incomplete consolidation (cooling) because of poor heating and diffusion which causes high void content.

If the manufacturing process is not optimized, insufficient interfacial bonding and poor consolidation could be formed. Consequently, this results in non-optimal crystallization degree, interlaminar strength degradation, excessive polymer degradation as well as the instigation of intralaminar and interlaminar porosity. Other quality challenges include fibre misalignments and a large amount of internal stress, another category of defects includes the geometry defects (gaps or overlaps and fibre bridging) and the presence of foreign bodies. Usually, these defects are rarely eliminated but can be modified by designing the part.

Therefore, quality control and assurance in composite manufacturing is vital in the planning, regulating and steady improvement of the processing quality. This also involves qualitative analysis of end parts which serves as a reference for subsequent manufacturing of parts. Although certain defects like delamination can be corrected in the post manufacturing phase, the quality of the part is substantially influenced in the manufacturing phase. Hence, the quality analysis of the part during manufacturing serves a vital function in the different processing stages viz. process development, qualifying and selecting the part during manufacturing and online material monitoring during the process. To ensure good quality is maintained throughout, it is beneficial to establish standards. It seems manufacturers neglect this so as to avoid competition and they utilize an internally developed quality assessment method which can eventually be a disadvantage. For thermoplastic composites in particular with aligned and continuous fibre reinforcements (e.g., sheets and tapes), there are scarce approaches to standardizing the quality process [133]. Presently, the majority of the monitoring and repair methods are manually done and are responsible for ~30% of the delay in processing time that substantially decreases the processing efficiency. The incorporation of on-line non-destructive monitoring into the entire process will result in more cost-efficient manufacturing. The progress of automated manufacturing should not solely focus on the development of online monitoring methods for the parts including TCP but should work pathways to achieve in-situ defect repairs. Domm et al. [133] were able to utilize the quality index for thermoplastic tapes (QITT) based on the automated fibre placement (AFP) process to identify and categorize the quality criteria into quality groups microscopic, macroscopic and mechanical as seen in Table 2.

For each category, varying methods of material analysis are used to quantify the quality values. The relationship between the varying quality values to a single value is derived through QITT as seen in Table 2. A decrease in a single numerical value enables a fast comparison to the suitability and quality of the tapes to be used in AFP process. The tapes are subsequently rewound and measured through laser scanners and optical micrometres. The resulting measurements were not only automated but also erased the effect of the manufacturing operator. Mack et al. [146] created a quality test rig utilizing QITT for an automated evaluation and assessment of the quality values for tape thickness, surface roughness and tape width. Based on the best practices described here, the quality control improvement should address the geometric factors and the utilization of post manufacturing treatment of filaments.

Another aspect to consider for automated manufacturing is that several processing data are produced in various processing phases by different components such as the design, consolidation and monitoring systems. The accumulation of these data facilitates the extraction of in-depth knowledge during the manufacturing phase that is utilized in a machine learning procedure [147]. Hence, Brüning et al. [147] have developed a novel method for acquiring and interpreting the processing data and also presented a software tool to assist in visualizing the detection of manufacturing flaws. The manufacturing set up incorporated the use of a thermographic process monitoring system placed at the consolidating head, sensors for monitoring the humidity, temperature and tow tension in combination with the means of estimating the remaining material amount from the supply element. The humidity and temperature are

Table 2
Categories for the quality analysis process for thermoplastic composites.

Quality index for thermoplastic tapes (*QITT*)		
Quality categories (Q_C)		
Macroscopic (*Ma*)	Microscopic (M_i)	Mechanical (*Me*)
• Consistency and accuracy of tape thickness • Consistency and accuracy of tape width	• Fibre alignment • Homogenous fibre distribution • Satisfactory impregnation • Consistency and accuracy of fibre volume fraction at all areas • Tape edge • Tape surface	• Tensile strength and stiffness • Flexural strength and stiffness • Interlaminar shear strength • Creep • Compressive strength • Impact energy absorption
Quality value (*Qv*) $QC_j \in [0,1]$; $\mathrm{QITT} = \sum_j QC_j = M_a + M_i + M_e = \sum_j \prod_i QV_{ji}$ $\mathrm{QIIT} \in [0,3]$		

ascertained and recorded within the laying head from the material supply element for the determination of ambient conditions surrounding the nip point during manufacturing. Therefore, pyrometers are utilized in the temperature control of the heat source and temperature measurement of the tow within the laying head. In addition, another pyrometer was used for monitoring the temperature straight from the front of the consolidation roller. Lastly, pressure sensors were applied in measuring the tow tension while the material amount remaining was detected using the ultrasonic distance sensors. This approach had some advantages based on a single reference processing setup with fibre reinforced polymer composite tapes and it was evident that the processing (device and material) greatly influenced the results. Hence, it was recommended that the specified data be properly obtained for the characterization of the automated process. Equipment such as infra-red cameras, image processing software, data storage and machine learning algorithms can be modified to suit various processes and materials. It is also crucial that these sets of equipment be optimized and utilized within a particular threshold. Furthermore, the peculiarities with the processing device like the reduction in the precision of their positioning can be naturally detected to be utilized for predictive maintenance through applying the obtained data from the processing of the various materials and manufacturing techniques.

Based on the conventional method of using thermal inspection in the compaction roller heads, Gregory and Juarez [139] analysed the obtained data to identify the defects. The in-situ process here involved heating the new ply from the substrate while an alternative rearrangement termed scan process which entails heating of the laminate from the top surface was introduced, but it was deduced that due to variations in heating arrangements, delamination was formed when it is hotter in the scans and colder for the in-situ scans. The scan process was more favourable as it was easier and more precise with constant tow orientation and feed rate which enabled the collation of data in a quick scan way. This method of data processing was able to be used in spotting regions of poor adhesion. Schmidt et al. [143] used a deep learning-based system in detecting and classifying induced defects to support thermographic online monitoring manufacturing process. Asides classifying these defects according to the material and size in this review, these defects were classified into material failures, manufacturing defects and foreign bodies. 12 varying deep convolution neural networks (CNN) with 3 different configurations were trained in accordance with the different data sets. The first type is composed of 10 hidden layers with a convolutional filter at a size similar to that of the thermal images. The second type comprises of 12 hidden layers with a square-shaped filter at size that increases as the CNN depth increases. The type 2 differs from type 3 as it is a very deep CNN comprising 22 hidden layers with small (3×3) convolutional filters. This investigation proved to be feasible in reliably monitoring thermal behaviours by detecting the defect categories at accuracy greater than 92% for the trained and validated data. The type 2 CNN was able to classify the defects at high accuracy irrespective of the image quality, particularly for the path monitoring. However, it was deduced that the monitoring system reliability increases when used in real applications due to the path-controlled monitoring configuration. Although the monitoring system can detect and categorize the varying induced defects during manufacturing, it is vital to retrieve the geometrical detail from the thermal images of the defects. Subsequently, either the operating personnel or the monitoring system will decide if it is critical to continue processing or repair the laminate. For further evaluation, the development of monitoring systems for foreign bodies and material failure should be considered.

4.5. Material testing standards and long-term performance qualifications

With the increasing demand for TCP, there is a need for more regulations and stringent quality guarantees as an indication of product quality. There has been a development of accelerated test methods for assessing the long time performance of composite materials. Basically, there are investigations of the failure modes for TCP but the formalization into standards or procedures remains to be done. There remains a need to improve the methodology for mechanically characterizing composite structure performance. Hence, the analytical and experimental impact of the material design should be thoroughly considered so that the output of this research will enable a better understanding of the material uniqueness and effect of sample geometry. The salient standard used in describing data for thermal and environmental performance is the ISO 2578/ASTM D3045 derived from the Arrhenius equation through extrapolating their long term stability. Although this standard is adequate, the results should not be extrapolated greater than the factor of four based on time. This is because the effect of the thermal and environmental factors will be hindered in terms of understanding especially the impact more than one mechanism can have on the general performance of the material [148]. In terms of the creep behaviour, few experiments on the flexural creep of fibre reinforced polymer structures have been conducted but most of the tests have concentrated on relatively short samples or small scale coupons at mainly short durations [149]. These tests are tensile longitudinal (ISO 527), flexural longitudinal (ISO 14125), compressive longitudinal (ASTM D695), compressive transverse (ASTM D695) and inter-laminar shear (ASTM D2344). Therefore, larger structural full-sized samples should be tested at longer times. To this effect, Sá et al. [149] attempted to validate the experimental study on the creep behaviour of the small scale pultruded tube coupons and beam test at a longer duration. Although there was an increase in deformation and significant creep recovery, the results are consistent for both types of material scale. This implies that small scale coupons can be utilized in predicting creep deformation of the fibre reinforced polymer profile.

Other standards are the ISO 10350-2 procedure for the acquisition and presentation of comparable data for several basic properties of polymers. This applies to reinforced thermoset and thermoplastic materials where the reinforcing fibres are either continuous (e.g., unidirectional, fabric or continuous-strand mat) or discontinuous with fibre lengths that are greater than 7.5 mm before processing. Contrastingly, the ISO 10350-1 specifically applies to unreinforced and filled polymers with fibre lengths of less than 7.5 mm. The ISO 14125 deals with the flexural test conditions for fibre reinforced polymer systems. It is an extension of the ISO 178 that includes both 3- and 4-point loading geometry and incorporates the conditions for fibre based composites. Although this method is suitable for fibre-reinforced thermoset and thermoplastic composites, it is not applicable in determining the design parameters but can be used for material selection or quality control assessment. This is attributed to differences between flexural and tensile properties which is due to

the material lay-up (structure). Based on sufficient validation derived from the relationship of laboratory scale tests to in-service performance, there is a plan to completely link standards to the aspect of durability [150].

A majority of the tested methods have been deduced to be useful in the determination of specific material properties through their additionto quality control and material qualification procedures. However, a complete validation that establishes the behaviour of composite materials is lacking currently, especially with the characterization of damage tolerance, compressive in-plane and inter-laminar shear properties [151]. Using ASTM D6641 combined load compression (CLC) test provides a good compromise between preventing early failure created by end crushing linked and reduction of stress concentrations linked with the final loading. The ASTM D7078 V-notched rail shear test with a large gauge section enables the enhancement of the load transfer capability. Due to the undesired combination of the stress concentrations and loading effects at the notched region, a large scattering of the shear properties will be formed. Therefore, there is a resolution of using correction factors for highly anisotropic composite materials with varying sample geometries. However, the ASTM D2344 short beam shear (SBS) test has displayed the capability of adequately evaluating composites and material qualification basis. Nonetheless, this procedure is unsuitable in deriving a design value that correlates to the structural analysis due to the undesirable contact and flexural stress build ups. Furthermore, the ASTM D7137 compression after impact (CAI) test is a famous procedure for ascertaining the damage tolerance characteristics of composites. The use of linear elastic fracture mechanics has been considered for the development of mechanical models that predict the critical threshold load for a structure at the delamination onset. The summary of these standards is displayed in Table 3.

Regarding the material qualifications of composite pipes for oil and gas applications, the ISO 20144 is a more detailed qualification and validation procedure for the calculation of the reliability and robustness of mostly thermosets (currently the major established matrix) across a variety of applications. Hence, this procedure is an improvement of the ISO10350-2 and can also be used in thermoplastics based on the established calculations and the derived property data. Herein, the technical aspect of the fundamental test methods covers the failure modes for a wide range of matrices and fibre types except for uncured thermoset materials. This procedure is the standard qualification plan (SQP) that is the minimal common test requirement for highly anisotropic composite materials. Further testing requirements will involve the extended qualification plan (EQP) that represents specific in-service aspects. Standard such as ISO 14692 covers the specifications, manufacture, testing and installation of glass-reinforced polymer pipes (including TCP) affiliated with offshore applications. Also, it proffers guidance and philosophy on the range of suitable applications for pipes and the limited definition of the materials used in the specified manufacturing. Another standard is the ISO 24817 used in ensuring that corroded or damaged pipes are externally repaired using composite systems at the qualification, design, installation, testing and inspection stages. An introspective look into standards indicates that a majority of the test methods for measuring the failure of polymer

Table 3
Summary of the benefits and disadvantages of the affiliating standards.

Standard	Benefit	Limitations
ISO 2578/ASTM D3045 (Thermal and environmental)	Thermal and environmental performance through accelerated ageing	Just one failure mode impact can be conducted at a time
ISO 527/ASTM D638 (Tensile)	Tensile properties for varying dimensions	Mainly accurate for isotropic and unreinforced polymers. Low repeatability
ISO 14125 (flexural)	Flexural testing specifically for fibre reinforced polymer. For thermosets and thermoplastics	Sensitivity to strain rate, sample and loading dimensions. Complexity in design parameter determination
ASTM D695 and ASTM D2412 (compressive and stiffness)	Compressive and stiffness properties. Thin samples prone to buckling failure can be used due to specified minimum sample thickness	Difficulty in obtaining consistency. The test can be categorized as complex
ASTM D2344 (short beam shear)	Short beam shear test for inter laminar shear properties. Cost efficient, fast and easy	Due to size of the short beam, large areas of uniform shear stress
ISO 10350-1 (acquiring and presentation of data)	Acquiring property data. For unreinforced polymers or reinforced polymers with fibre length <7.5 mm	Inappropriate for fibre reinforced polymers with fibre length >7.5 mm
ISO 10350-2	Acquiring property data. Applicable to both thermosets and thermoplastic polymers For reinforced polymers with fibre length >7.5 mm	Inappropriate for reinforced polymers with fibre length<7.5 mm
ASTM D6641 (combined load compression)	Combined load compression analysis. Adequate for failure prevention. Relatively inexpensive, small and simple. Higher load transmission than shear loading. Can be used in larger and thicker samples. Adaptable to ductile thermoplastic matrix	Specific tools for sample end required. Sensitive to thickness variations
ASTM D7078 (V-notched rail shear test)	Notched rail shear test. Efficient ability of load transfer	Formation of large scattering at the end of sample due to stress concentration and loading.
ASTM D7137 (compression after impact)	Compression after impact. Obtain damage tolerance characteristics	Suitable for samples with thickness > 4mm
API RP15S (2006 edition) (Reinforced composite pipe qualification)	Simplified qualification process	Requires a long term pressure test (10,000 h)
DNV GL-RP-F119 (TCP qualification)	Suitable for TCP	Complex procedure as material properties, calculations, analysis and finite element analysis is needed.

matrices investigate a single failure mode in isolation.

However, this can be inaccurate but a sole contradiction to the earlier stated isthe use of de-rating factors to ascertain the material resistance. The most sceptic aspect of the de-rating factor is their efficacy in determining the long-term performance of the material is not consistently evident. Industrially, although accelerated test methods have been previously used for polymer based composite materials, significantly few have satisfactorily recommended the validation of these test methods. To be specific, adequate quality validation procedures for long term testing for both laboratory scale and recovered parts from in-service use are absent. Narrowing the qualification requirements of reinforced pipes to industrial standards, most qualifications were initially based on modified API RP15S (2006 edition) that was made suitable for offshore applications based on hydro testing.

Recently, the DNV GL-RP-F119 has been developed as the recommended practice for TCP. Although both specifications offer long term performance qualifications, they have different design and qualification requirements for reinforced polymer pipes. The most recent study conducted by Putra et al. [152] deduced that the API RP 15S is a simpler approach but that the need for long-term pressuring of up to 10,000 h will impede the growth of the piping technology. Although the differences in the failure pressure value between the 6,000 h dataset and the 10,000 h dataset are not significant for the designed life of a short (missing word?), it will be helpful to utilize shorter qualification timelines. In considering longer design timelines, the 10,000 h long term test should still be in use. However, it is not advisable to derive the maximum pressure rating of the reinforced pipe from the shorter testing durations lower than 6,000 h as the failure pressure value can substantially be overestimated. Noteworthy, both of these qualification procedures are yet to be globally adopted and utilized. Hence, it is necessary that manufacturers, industry stakeholders and end-user(s) of the pipe should share results, and experiences or conduct collaborations. This will expedite the development and adoption of this piping technology and consequently, there will be increased reliability, safety and user confidence degrees for advanced offshore applications.

4.6. Concluding remark

This review has highlighted the current state and challenges associated with characterizing manufacturing induced defects in TCP and pathways to apply in-situ characterization during the process. It can be deduced that there is a correlation between manufacturing process to the performance of the final part and the selection of characterization technique as well as optimizing process parameters. This review aims to provide the presently available consolidation monitoring systems that have potential for in-situ means of characterizing the manufacturing induced defects and also increase the life span of the TCP. Fibre misalignment, voids and poor consolidation were identified as the major manufacturing induced defects to be emphasized while for in-service defects, delamination was identified which has a direct link to the manufacturing induced defects. Furthermore, this review indicated an enormous potential with modern advancement of consolidation monitoring systems for thermoplastic composites with a major challenge being the transferability of knowledge from the most common thermoset composites. The outlook for the on-line monitoring approach to ensure process optimization and quality control has been presented in this review as well as the adoption of machine learning for an efficient manufacturing process through the detection and classification of defects.

A subsequent review of this research will seek to determine the consequence of the adhesion and interfacial bonding mechanism, material crystallization, thermal degradation, and thermal residual stress on the general properties of the TCP based on available state of the art literature. This review has attempted to bridge the gap but more investigation is required for significant improvements and sustainability in this ever-evolving subject of composite pipe manufacturing. Evidently, there has been a tremendous advancement in equipment used in performing thorough and precise experimental analysis with faster computing systems that enables the performance of complex simulations and modelling. However, more effort is needed to entirely upscale this to an industrial scale. The improvement of the consolidation process to meet or even surpass the autoclaved counterpart and enhance the production level are the salient challenges to be addressed in the bid to resolve the issue of upscaling. Furthermore, the future of automated processing data analysis will evolve to introduce more analytical methods such as automated clustering and data set filtration (denoising). Additionally, the QA results (data from monitoring) should be equivalent to the designing and processing data to strengthen the quality of all the generated models. Research on the TCP regarding online monitoring systems during manufacturing remains a grey area and the goal is to make headway on this challenge.

Author contribution statement

All authors listed have significantly contributed to the development and the writing of this article.

Data availability statement

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

Declaration of competing interest

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

Acknowledgement

This report was made possible with the support of the Scottish Research Partnership in Engineering (SRPE, project no. NMIS IDP-034; Project Title '*Characterization of Manufacturing Defects in Thermoplastic Composite Pipes*') in a collaboration project. The data used, observations made, and views expressed are solely the responsibility of the authors.

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