Article:

Collinson, M.G. orcid.org/0000-0002-4855-1878, Bower, M.P., Swait, T.J. et al. (3 more authors) (2022) Novel composite curing methods for sustainable manufacture : a review. Composites Part C: Open Access, 9. 100293.

https://doi.org/10.1016/j.jcomc.2022.100293

Composites Part C: Open Access 9 (2022) 100293

Contents lists available at ScienceDirect

Composites Part C: Open Access

journal homepage: www.sciencedirect.com/journal/composites-part-c-open-access

Novel composite curing methods for sustainable manufacture: A review

MG Collinson [a,*], MP Bower [a], T J Swait [a], CP Atkins [a], SA Hayes [b], B Nuhiji [a]

[a] University of Sheffield Advanced Manufacturing Research Centre, AMP, Wallis Way, Rotherham, S60 5TZ, United Kingdom
[b] Department of Multidisciplinary Engineering Education, University of Sheffield, 32 Leavygreave Road, Sheffield, S3 7RD, United Kingdom

ARTICLE INFO

Keywords:
Carbon fibre composites
Rapid cure
Electromagnetic radiation
Joule effect
Review
Low power

ABSTRACT

The curing of high-performance carbon fibre composites has not changed significantly since their inception, primarily using ovens and autoclaves. To reduce energy costs and continue to increase throughput, alternative novel curing methods that heat the components more directly by not relying on convection or conduction have been investigated frequently, at varying levels of success and scale. This paper critically reviews direct electric, microwave, induction, and radio frequency heating for their manufacturing and engineering applicability, overall energy consumption and evaluation of future challenges and opportunities for these methods in industry. It highlights some of the benefits such as high heating rates, ability to control exothermic reactions effectively and low power consumption, as well as some of the remaining challenges to common adoption, such as uniform degree of cure and ease of use.

1. Introduction

The use of composites in the aerospace and automotive industries is becoming increasingly prevalent, due to their high specific stiffness and strength [1]. They however are limited to high value industries due to their relatively high cost of raw materials and manufacture. International legislative measures aimed at achieving carbon neutral growth from 2020 onwards has driven the necessity of light-weighting vehicles to reduce carbon emissions [2,3]. This has led to greater utilisation and investment in composite materials, particularly in the transportation sectors of aerospace and automotive [4,5]. This increase of interest in harmful emissions has led to increased scrutiny of the emissions of the manufacturing processes associated with these weight saving materials.

Manufacture of the raw materials has the highest energy cost, with carbon fibres (CF) requiring 183-286 MJ/kg, epoxy resin 76-80 MJ/kg and pre-preg process 40 MJ/kg. This can mean in the worst-case scenario, 1 kg of CF could have an energy footprint of at least 223 MJ/kg before it has been cured [6]. Autoclave cure has been estimated to be around 20-22 MJ/kg [7], which accounts for less than 10 % of the total energy consumed in the manufacturing process up until this point. However, it is still important to remove energy intensive processes from the supply chain where possible.

Despite the through-life energy savings of a lightweight component [8], the total embodied energy can have a costly environmental impact [9,10], and significantly reduce the previously gained in-service benefits.

To improve the energy efficiency during composites manufacturing, alternative cure methods that can deliver power directly to the composite need to be considered. Example methods that are covered in this study include microwave (MW), magnetic induction, radio frequency (RF) and direct electric cure (EC) [11]. Novel curing methods are experimental and have challenges to overcome before implementation [12,13]. Many of these methods rely on the composite exhibiting electrically conductive and Electromagnetic (EM) susceptible properties to generate heat within the part. This method of heating from inside of the composite can be described as volumetric heating or inverse thermal gradient curing. Carbon fibre reinforced polymers (CFRP) exhibit non-isotropic electrical performance due to the contrast in conductivity between the conductive CFs and an insulating matrix. This can cause uneven heating patterns using these methods [14–16]. These properties can contribute to uncontrolled heating modes and therefore uneven degree of cure (DoC) across a component. Other issues include the difficulty of setup over existing methods, not being universally compatible with all geometries due to lower technology readiness level (TRL) [17] and are not yet turnkey solutions.

All these heating methods have challenges to their implementation, which if these can be overcome, can provide significant benefits over existing manufacturing methods. These benefits include lower power requirements, higher heating rates for reduced cure times, and the flexibility to deliver energy to a targeted location in the component [14].

* Corresponding author.
E-mail address: m.collinson@amrc.co.uk (M. Collinson).

https://doi.org/10.1016/j.jcomc.2022.100293
Received 25 April 2022; Received in revised form 27 June 2022; Accepted 27 June 2022
Available online 3 July 2022

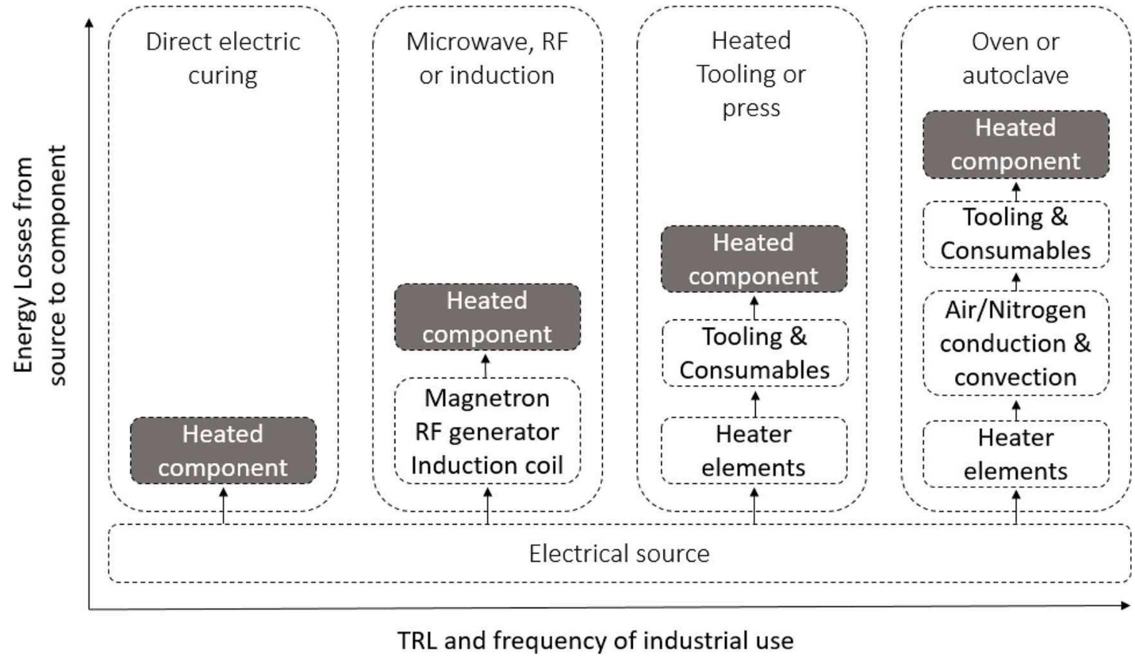

Fig. 1. Diagram to illustrate the energy flow in existing and new composite manufacturing processes, demonstrating the high losses in existing processes and the opportunity provided by novel cure methods.

This is in comparison to autoclaves and ovens that have large thermal masses and slow ramp rates, which add to energy consumption, time and cost during production [18].

This paper reviews the state-of-the-art for novel composite heating and curing methods, outlining their heating performance, practical considerations for manufacturing and overall energy efficiency. Current performance, challenges and potential future opportunities for implementing these curing methods are reviewed, considering existing manufacturing methods, materials and specific end-use cases.

1.1. Curing of composites

To compare novel heating and curing systems, the heating response of the composites being manufactured needs to be understood. Epoxy resins are the primary system covered in this review, as high temperature and/or pressure processes are required to achieve high mechanical performance. External thermal input is necessary to:

- Reduce viscosity of the resin;
  - to ensure full wet-out and adhesion to reinforcement
  - to allow voids to exit
  - to allow the resin to flow out of the part and increase the fibre volume fraction
- Ensure crosslinking occurs and the gel point is reached
- Accelerate crosslinking and therefore reduce cure duration
- Raise the glass transition temperature to the level required [19]

Conventional heating is supplied by convection in an oven or autoclave, which has the advantage of applying homogenous temperature to the component. Most composite matrices, from polyester resins for low cost and performance composites, to epoxy resins for higher performance, cure in an exothermic manner [20].

The primary matrix material discussed in this review is epoxy resin, which can have a wide variety of properties depending on the use case, before and after cure. If formulated for an adhesive, it can come as a film, or as a paste with a viscosity as high as 700 Pa/s. As a matrix for carbon and glass fibre composites, it can range from 20,000 Pa/s for vacuum assisted resin transfer moulding resins, or 1200 Pa/s for use in filament winding applications [21]. Glass transition and service temperatures of these resins depend on the final use case requirements, automotive resins can reach up to 130°C, with aerospace resins reaching up to 200°C.

In minor cases of exothermic reactions, local areas can be overheated, leading to residual stresses within the part [22–24]. Failure to control the heating rates, and thus achieve the required structural performance can lead to premature part failure [25]. In extreme cases, the resin can self-ignite, damaging the component, and potentially the tooling and associated curing equipment, in addition to releasing toxic smoke [26].

To ensure that uncontrollable exothermic reactions do not occur, reducing ramp rates up to the final cure temperature, and increasing dwell times are common strategies. If a composite is made thicker or has a reactive resin, then the heating rates will need to be reduced further and dwells made longer [27], to reduce the exothermic peak. Resin and pre-preg manufacturers have to therefore account for a large range of composite geometries consisting of thick ply composites, thicker than 12 mm, in less-than-optimal cure environments (i.e. tooling with low heat transfer coefficient, and convective heating hotspots).

A homogenous DoC is desirable to achieve consistent mechanical properties but to maintain costs manufacturers require this to be achieved in the shortest time possible [28], which works against the desire to avoid exothermic reactions. An issue for ovens and autoclaves is that even if the air temperature is controlled from the component temperature, due to the high thermal mass of the internal cavities, the component temperature cannot be controlled quickly enough to stop an exothermic reaction [29]. With these novel curing technologies, the power input to the reaction can be instantaneously switched off, leading to a greater degree of control over the cure. This allows increased protection against exothermic reactions and enables greater control for reactive or predictive control cure cycles to be used.

1.2. Introduction to novel curing methods

Cure cycles defined by resin and pre-impregnated composite manufacturers are significantly longer than is required for many components, resulting in energy inefficiencies [30]. Fig. 1 illustrates the method by

Table 1
Overview of cure methods reviewed here, their pros and cons, and references to previous studies on these heating methods.

Heating type	Advantages	Challenges	Reference
MW	• Energy efficient heating process • Non-contact method • Heat generated within the component	• Arcing, localised heating and burning can occur • Particular health and safety requirements • Requires compatible consumables • Potential high capital cost of commercial MWs	[15,16,31, 33–36, 53–74]
Electric Cure	• Energy efficient heating process • Lower void content and higher flexural modulus components	• Requires electrode contact on, or within the component • Electrically insulated tooling required • Specific component setup required • Localised heating and burning can occur	[14,32,37, 38,75–89]
RF	• High energy efficiency	• Large knowledge gap concerning composites	[49,90,91]
Induction	• High heating rates • Not RF based so low health and safety requirements	• Specific coil design required for each heating pattern/ component geometry • Inductor coil must be close to the heating area	[51, 92–103]

which electrical energy is converted to thermal energy for a variety of traditional, emerging and novel composite manufacturing techniques. Oven and autoclave are the least direct methods, with heated presses improving on these, with respect to energy efficiency per part. The stage of development of these technologies is also reflected in the TRL used to determine a technologies state of development and use in manufacturing environments.

Novel curing methods can be characterised as using heating methods that bypass, or significantly reduce, convective and conductive heating. These methods have the potential to achieve greater manufacturing energy efficiency, a higher degree of control and therefore the ability to cure composite components quicker leading to further energy savings. Other specific benefits can include;

- MW cure - the ability to only cure certain areas on a part [31],
- Direct electric cure - to produce overall lower void content composites [14] and
- Induction cure - the ability to heat at hundreds of degrees per minute [32]

These technologies can have unique advantages over conductive heating methods, resulting in substantial research in this area [11,14,15, 31–39], (summarised in Table 1). Widespread adoption within industry is limited due to significant technical challenges that have not yet been solved, where turnkey solutions are required. A summary of the advantages over cure methods and current challenges for each heating method can be found in Table 1.

Other heating technologies can provide some of the previously described benefits to composite manufacturing, such as Infra-red (IR) [40,41], laser [42] and flash lamp systems. These technologies only heat a very specific area and need to be combined with other automated technologies such as Automated Fibre Placement (AFP) [43] or filament winding [44] to realise their potential. They are used as a preheating technology for single plies as they are only able to heat the surface. In the cases of laser and flash lamp systems, they are only able to heat in a very localised area, i.e. not the bulk component, and can be prohibitively expensive to acquire.

Other bulk curing technologies have also been discounted as a part of this review, such as Ultraviolet (UV) curing and frontal polymerisation. UV curing requires specific resins that can be polymerised by UV radiation. For this reason, they can be cured at low temperatures and be cured rapidly under the correct conditions. Common use cases in the composites industry are filament winding and gel coats, due to UV requiring line of sight and having limited depth penetration [45] Frontal polymerisation is a very promising technology, as there is an opportunity to cure large volumes of composites with very little initial energy input, however there is little literature available on composite

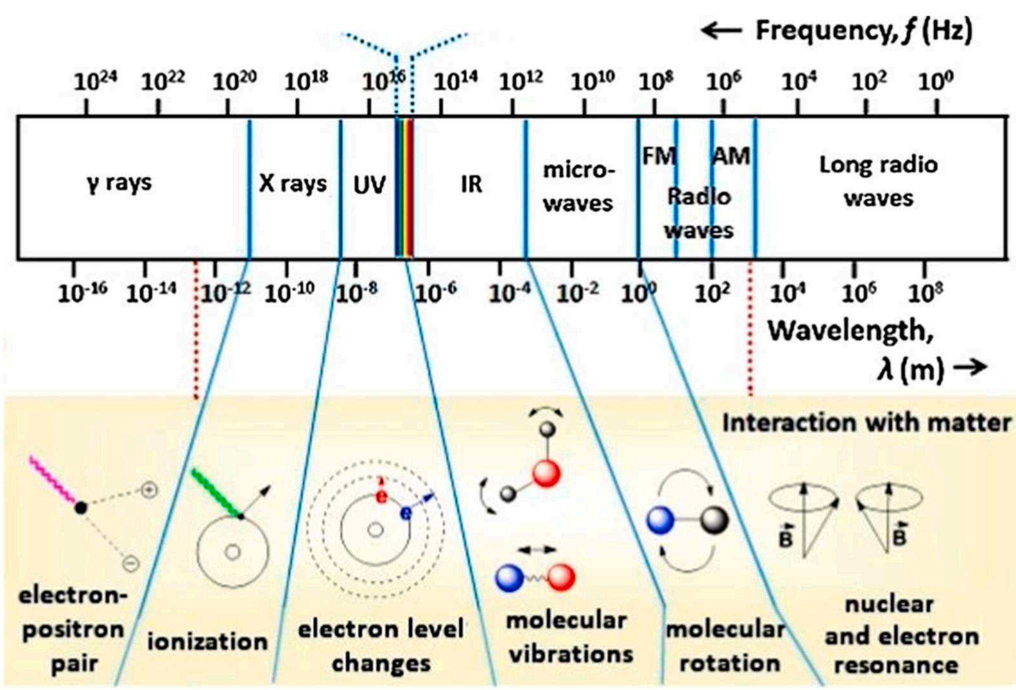

Fig. 2. - EM spectrum [52]

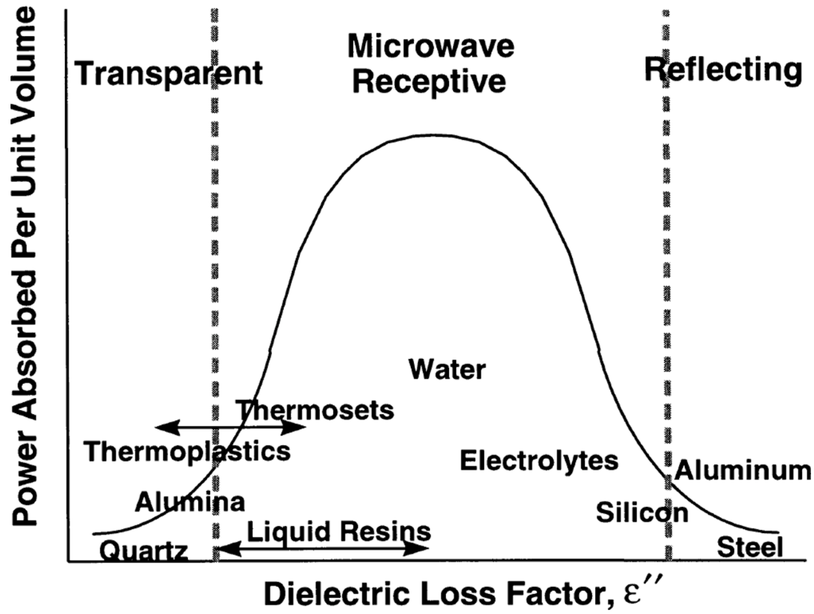

Fig. 3-. MW receptivity: The variation of power absorption as a function of dielectric loss factor (2.45 GHz) from the figure in Thostenson & Chou [69]

applications. Robertson et al [46] demonstrated resins suitable for frontal polymerisation in 3D printing and CF curing applications. With very little energy input, less than 20 W, it was possible to cure a 100 × 200 mm panel in less than 5 minutes with a polymerisation rate of 98 mm/min. Goli et al [47] modelled the frontal polymerisation effect on unidirectional (UD) composites, finding that increased fibre volume fraction increased the speed of the polymerisation front, also observed by Robertson et al. This was due to the thermal conductivity of the fibres assisting heat transfer over the composite. This research shows that frontal polymerisation is a promising curing technology, suited for composites, however, isn't yet commonly available.

1.3. Novel cure methods overview

There are two main ways that novel cure methods generate heat within a composite:

1 by the absorption of EM radiation - MW, RF and IR energy are all on the EM spectrum (Fig. 2) and are generated by passing alternating current along a conductive material, which can be in the form of a magnetron for MW [48], field applicator for RF [49] or lamp for IR [50].
2 by generating electron movement to induce the joule effect - Induction heating uses an alternating current to generate a local EM field which induces a flow of electrons in a material [51]. Like induction, direct electric cure relies on the movement of electrons to generate heat, although it is applied directly through contact electrodes. This movement of electrons induces the Ohmic heating effect, or Joule effect within the fibres, allowing for the composite to be cured.

An overview of all the cure methods covered in this paper is outlined in Table 1, summarising their advantages and disadvantages with respect to their practical implementation in industry, TRL and part quality.

2. Novel cure methods review

In the following sections is an in-depth review of the novel cure methods identified in Table 1.

2.1. MW curing

2.1.1. Background to MW processing

MW curing of polymer matrix composites is a method of heating composite materials using EM radiation in the MW spectrum [53,104]. The early research into curing composite materials using EM radiation found that cure cycles could be reduced and optimised for MW curing applications [54,55,104]. The reduction in cycle time was attributed to the volumetric nature of MW heating. Lee and Springer [53] particularly focused on creating a model of the curing process which captures the temperature distribution, resin viscosity and fibres. Using these inputs, the DoC of the resin, the void content and residual stresses were calculated and experimentally validated. The study uses an experimental methodology to validate these findings. This early work shows the importance of understanding material properties when MW processing materials. Lee and Springer list several key parameters: Dielectric constants, thermal conductivity and DoC as a function of temperature.

Thostenson and Chou [69] presented a detailed review of previous MW processing literature. They state that the MW field and dielectric response of a material is critical to the ability to heat using MW power. Therefore, understanding the dielectric response of materials is required to optimise the heating process [65]. The key points highlighted by the authors include:

1 When materials are incident to MW radiation but have different dielectric properties. The MWs will selectively couple with the higher loss material.
2 Non-uniformity within the EM field will result in non-uniform heating. This point is important for closed-cavity systems where standing waves are generated due to constructive and destructive interference.
3 Dielectric properties change with temperature, therefore the ability of MW's to generate heat varies during the curing process.

Fig. 3 is a graphic representation of how the dielectric loss factor affects power absorption. It shows how power is absorbed in a material as a function of the dielectric loss factor at a particular frequency. The dielectric loss factor forms an upper and lower bound on power absorption in a material through two different mechanisms: transparency and reflectance. A material is transparent when incident EM radiation passes through the material with little to no absorption which occurs in materials with a low dielectric loss factor. Conversely, a material is reflective when incident EM radiation is reflected off the surface of the material before being absorbed. This phenomenon is most prominent in materials with high dielectric loss factors.

The authors also detail an equation for power absorption per unit volume [69]:

$$P = 2\pi f \varepsilon'' E^2 \tag{1}$$

where P is the power (W), f is the frequency (Hz) of the EM radiation, ε'' is the dielectric constant and E is the EM field strength (V/m).

However, as the energy is absorbed into the material, the electrical field strength reduces. Therefore, a penetration depth can be defined, which is linked to a reduction in power in the material by 1/e (Euler's number) compared to the surface power [69]:

$$d = \frac{c\varepsilon^0}{2\pi f \varepsilon''} \tag{2}$$

where d is the penetration depth (m), c is the speed of light in a vacuum (m/s) and ε^0 is the dielectric constant of free space. Power absorption is also affected by penetration depth, exponentially decaying via the following relationship [105]

$$P(x) = P_0 e^{-2\alpha x} \tag{3}$$

Where P(x) is power dissipated at depth x, P_0 is the power at the surface and α is the attenuation constant, which is a function of wavelength (m), loss tangent and relative dielectric constant. It is noted that Eqs. 1-3 do not include magnetic losses.

These two equations highlight the importance of understanding the material properties of the composite, as the power absorption and penetration of the MWs are heavily dependent on the dielectric loss factor.

2.1.2. MW processing of composite materials

A summary of some of the key experimental MW studies covered in this review are in Table 1. This review mainly covers thermosets, however a review and comparisons of thermoplastic and thermoset MW processing was published by Naik et al [106].

Mishra and Sharma [109] conducted a detailed review of the MW heating phenomena in a variety of materials including polymer composites. The authors highlighted the difference in heating mechanics relating to the fibre type. In low conductivity fibres (such as glass or aramids), the heating mechanism is dominated by the resin system. However, many resin systems have low dielectric loss factors meaning the heating rate of the cure will be reduced. Alternatively, fibres with high conductivity (such as CFs) absorb the MW radiation rapidly and heat quickly. This phenomenon is less understood, but the authors speculate that the alternating EM field induces an electric current into the fibres. The fibres then heat due to the Joule heating effect.

Kwak et al [56–58] detail the potential advantages of MW curing of composites: rapid heating, volumetric heating, selective heating, self-limiting properties, and reduction in non-conforming parts. The authors discuss the main issues of MW processing including inhomogeneous energy distribution, arcing, tooling design and understanding of the 'MW effect' that improves interfacial bonding and glass transition temperatures. Kwak emphasises the importance of the dielectric properties on the MW curing process and reviews how the dielectric material response is dependent on several variables:

- Dielectrics as a function of frequency: The dielectric response varies as a function of frequency [110]. Materials peak at a dielectric resonance at a specific frequency. Therefore, to maximise MW heating the appropriate frequency should be selected (i.e. water resonance at 2.45 GHz).
- Dielectrics as a function of the DoC [111]: As the resin system begins to cure, the dipolar molecules are restricted, and this can reduce the dielectric heating effect of the MW.

The key aspects of MW curing that need to be explored further are: characterisation and material properties, specific tooling, process control and simulation.

Xuehong et al [60,61] conducted two cross-platform studies into MW versus thermal curing. The study [60] found a reduction in the cycle time of 63 % using MW curing optimising the process by adjusting input power (W) and radiation time (s). The final void content and ILSS properties were also found to be equivalent between each platform. Xuehong et al [61] also found a significant increase in compressive strength of composites cured using MWs compared to autoclave cured equivalents. The improvement in compressive strength was attributed to the superior interfacial adhesion between fibres and resin, which was attributed to the volumetric heating, despite the higher porosity of these samples.

Papargyris and Day [62] used MW assisted RTM to achieve a 50% reduction in cycle time compared to the conventional curing process. The study found both processes produced similar flexural moduli and strength, with the ILSS of the MW cured composite outperforming the autoclave process by 5 MPa (9 % increase). However, Nightingale and Day [59] found a reduction in ILSS and flexural properties of MW produced composites. This finding was attributed to the high void content of MW cured composites (ranging from 9 – 19 %). The authors stated this was caused by a lack of consolidation and the void forming a crack initiation site.

Yusoff et al [63], compared MW RTM to conventional RTM. They found a reduction in cure cycle time (between 30 – 60 %) using the MW process however composites exhibited much higher void content. These findings suggest that the rapid curing process has reduced the time to allow volatiles to escape the resin, leading to voids being trapped.

Li et al [64] investigated the induced strains associated with thermal and MW curing on 'L-shaped' CF bismaleimide composites. The MW curing process led to reductions in cycle times and the DoC between the two platforms were equivalent. The MW cured composites recorded a low strain throughout the cure and therefore had less spring-back of the 'L-shape' once cured. Li et al associated this with CFs' high dielectric loss, indicating that the MW process heated the fibres directly. The surrounding resin is then heated through conduction leading to a coefficient of thermal expansion mismatch.

The literature relating to suitable tooling materials can be separated into laboratory and industrial scale materials. On the laboratory scale, glass quartz [65] and Polytetrafluoroethylene (PTFE) [53,62] are commonly used due to their low dielectric properties. By using low dielectric tooling, the MW can be absorbed by the polymer matrix composites thereby improving the curing efficiency. Although glass and PTFE are suitable for the laboratory scale, the materials cannot be used on the industrial scale due to their brittleness, poor machinability, and cost. The studies where large tools have been used are predominately flat plates of quartz glass in a highly controlled environment [66]. Metal tooling [56,57] has also been used for more complex tools but has the disadvantage of reflecting MW energy which can cause arcing. The metal tooling can also act as a heat sink that limits the heating of the composite component.

The literature about MW cured composites generally finds that properties are equivalent to conventional curing processes. However, it is difficult to compare as very few of the studies encompass all aspects of composite characterisation. Void content has been highlighted as critical to the performance of MW cured composites. For out-of-autoclave processes such as MW heating, void content is linked to the quality of the vacuum on the part. Hence, developing a consistent process is vital for the efficacy of the MW process.

Energy consumption of the microwaving of composites for curing has not been characterised fully yet. Many of the previous studies have

Fig. 4. - Vötsch MW system at the AMRC [112]

Fig. 5. - Robotic MW cell at AIMPLAS pilot plant developed during the WAVECOM project [71]

highlighted the opportunities to reduce the length of the cure cycle but have not yet linked directly to benefits in reduced energy consumption. Many papers indicate the maximum power of the magnetrons and indicate what power percentage levels they were used at during the cures, however, do not indicate total power usage. Thostenson and Chou [65] do briefly discuss power usage during a 3-hour cure, which is estimated to be 1.13 kW/hr. However, the dimensions of the component are not fully specified, which makes it difficult to compare against other curing methods.

2.1.3. MW curing methodologies and use cases

Numerous scientific publications have investigated MW curing of composites closed cavity magnetron systems, as discussed in section 2.1.2 [15,31,56,57,67,68]. The closed cavity MW systems consist of a sealed metallic chamber that contains any MW energy that is emitted into the chamber. The MWs are reflected off the cavity walls until they are either absorbed by the component or attenuated in the cavity. The MWs are generated using magnetrons and then transmitted towards the cavity using waveguides.

A commercially available industrial MW heating platform used throughout the field is the Vötsch HEPHAISTOS system (Fig. 4). The MW consists of a large closed hexagonal cavity and operates using a magnetron/ waveguide system [68].

Nuhiji et al and Green et al [15,31,67] used a Vötsch system to explore the control and temperature monitoring of MW processes. They modelled the MW system heating process and investigated novel tooling materials suited to MW processing. Of this research, the main highlight is the effectiveness of the MW curing processes and the potential energy savings available when upscaling the technology to within TRL 5 or 6.

Kwak et al [56,57] developed a dedicated composite manufacturing process using the Vötsch system and have created a consistent process method for manufacturing composites. The methodology developed enabled the measurement of MW penetration depth and the characterisation of composite properties. The composites produced were of equivalent quality to that expected of autoclave produced composites.

Kwak et al [58] also developed a closed cavity MW which included a pressure vessel. The system has 96 magnetrons supplying MWs at 2.45 GHz, however, limited information is published on this technology. Hang et al [70] developed a bespoke closed cavity octagonal MW to process polymer composites with a maximum power of 5 kW.

To summarise, the closed cavity MW systems reviewed present several limitations challenging the technology:

1 Fixed frequency and 'closed cavity' design: Despite the unique cavity designs, the MW system is still susceptible to the generation of standing waves. This causes inhomogeneous heating during the curing process, which can lead to poor part quality. This phenomenon is complex and based on the interaction between the MW frequency, composite materials, tooling, consumables, metallic trolley, and magnetron phase.
2 Cavity size: This can limit the part size and lead to batch processing, although is mitigated by the improved cycle times.
3 Arcing: Exposing the edges of conductive fibres to MW energy within the cavity can lead to issues with electrical discharge. This has the potential to damage the vacuum bag or component leading to scrapping of the part.

Concentrated efforts by industrial and academic consortiums have been made on the mounting of MW heating systems onto robotic arms

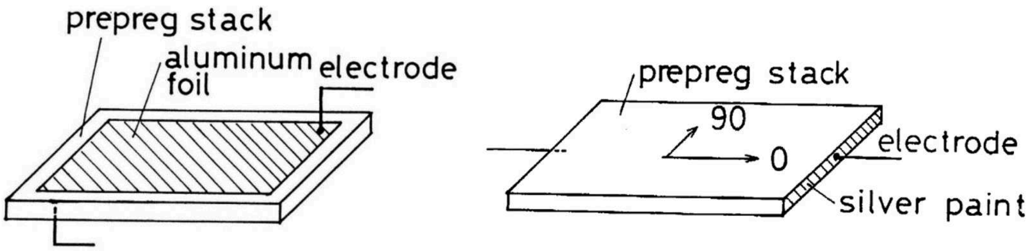

Fig. 6. Initial electrode positions identified by H. Fukuda [76] suitable for electric cure.

for localised heating of composites. Rudolf et al [113,114] developed a robotic arm MW system, alongside a resin functionalised suitable for MW energy absorption.

It reports that the MW system led to 'a strong improvement of degree of polymerisation' as tested using Differential scanning calorimetry (DSC) and highlights how a lightweight antenna system was developed to enable complex geometries of components.

E. Díaz et al investigated the use of MWs to cure composites with an integrated robotic system as part of the WAVECOM project [115]. They investigated susceptors to enhance absorption of MW radiation and monitored residual stresses and distortion using FBG during curing.

Trials were conducted using the robotic arm and a 2000 W magnetron (2.45 GHz). A cylindrical type antenna was used inside an isolated cell (Fig. 5), where susceptors improved the curing process and enhanced the degree of polymerisation [71]. Borrás et al. [116] highlight the improvements in heating efficiency by adding 1 % carbon nanotubes and identify how the dispersion of the nanotubes is vital to homogenising the heating pattern.

Zhou et al [107,108] used frequency-selective absorption films to generate heat in localised areas to enable easy to control zonal heating of composites. Films with absorption of 915 MHz and 2.45 GHz were used, alongside their respective MW sources at the same frequencies. This enabled the thermal control of two independent zones, allowing even temperature distribution in standard, or non-uniform thickness laminates.

Researchers have implemented MW heating in an RTM closed mould process [72]. The resin system is preheated (using MW heating) and injected into the mould cavity, the injected resin is then heated via a secondary MW source, to assist with issues with achieving homogenous heating in the tooling.

MW curing has the opportunity to be applied in a high range of applications that are currently served by autoclaves or ovens. The controllability of high heating rates shown in most studies allow for significant cycle time reduction and an increase in mechanical properties. Naik et al [106] discuss that these properties ensures that it is economically viable, particularly in aerospace. It will likely take industry a lot longer to adopt over existing methods due to cost and required technical know-how to ensure high quality parts are produced.

2.2. Direct electric curing

Direct electric cure uses the low electrical resistance of CF composites as the heating element through the exploitation of the Joule effect. In literature, this method has also been called Joule effect cure, electric heating and self-resistance curing. By running current through the fibres and inducing the Joule effect, the component itself acts as a heating element to cure the matrix. Epoxy matrices used in most studies reviewed are insulators [117], which therefore inhibits Joule heating by increasing the contact resistance between an electrode and the composite. Electrically conductive resins modified with nanoparticles to increase electrical conductivity are of interest in this area of research, discussed more generally in Section 3.3.

2.2.1. Background to Joule heating composites

When using CF, or a single tow bundle as a heating element, the fibre can act as a continuous resistor, and therefore heat is generated evenly along the length [77,80]. PolyAcryloNitrile (PAN) fibres have low electrical resistance due to the graphitic nature of the fibres, with a 12K tow having a resistance value of around 18 μΩ.m at 25°C. A reduction in resistance of 3.2 % can be observed as the temperature increases to 150°C [77]. This introduces a time dependency to the power requirements of this cure system.

In any long fibre carbon composite, conductivity is lower in-plane (along fibres), compared to through thickness [92]. Electron transfer is primarily in the fibre direction, 200x more than across the thickness of the fibre, and increases with fibre volume fraction [118]. Any fibre-to-fibre crossover has a very small contact area and will have matrix around it which is commonly dielectric [92], leading to high electrical resistance between fibre plies. Current applied through an electrode will only primarily heat the plies in direct contact, with the resistance between plies limiting electrode transfer and subsequent heating [119]. Contact resistance between the electrical source and the composite needs to be lower than the resistivity of the composite, or the electrical contacts will heat up at a higher rate than the composite itself. This limitation restricts electrode layouts for electric curing and further complicates Joule effect heating patterns.

Table 3 contains a summary of studies on direct electric cure, covering a range of manufacturing scenarios and applications specific to heating the manufactured component. Key electric curing parameters such as material type, electrode configuration and resulting heating performance are highlighted. As there is a large range of testing methods, material types and geometries, a summary of key results of the studies is presented, with respect to being a viable future manufacturing method.

2.2.2. Direct electric cure of composite materials

H Fukuda [76] was one of the first to introduce current into CF pre-preg stacks (TORAYCA P3060) to reach a curing temperature of 180°C. Through thickness and edge to edge were identified as electrode positions, seen in Fig. 6, which set out a standard and repeatable method for electric cure.

Heating of plies with through thickness electrodes provided poor temperature uniformity, of which an example can be seen in Fig. 9 (e). It was not used further in their study and has only been a suitable way to Joule heat in very specific cases, as demonstrated by Reese et al. in a modified industrial composite press on 3D woven architectures that had specific through thickness fibres [82].

Edge to edge curing of 150 mm x 50 mm, 16 ply stacks was more successful, reaching the desired cure temperature, however it was only monitored and controlled from one foil type thermocouple. These were compared to autoclave-manufactured samples, achieving around 78-90 % of the bending strength. It was observed that due to the low resistance of the fibres, the current required to reach 180°C was significant (~100 A) and the voltage less than 10 V, leading to a requirement of high current, low voltage power supply units for electric curing large geometry components.

C. Joseph et al [75] modified the edge-to-edge curing method, by

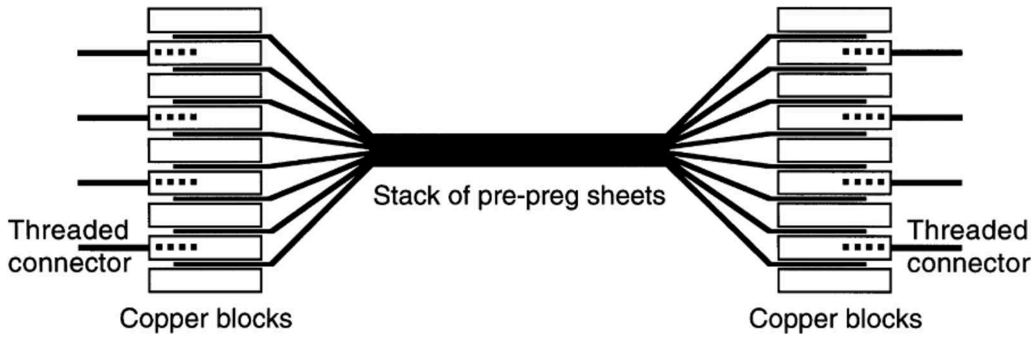

Fig. 7. Example setup used by C. Joseph et al [75], with individual ply pairs having dedicated electrodes.

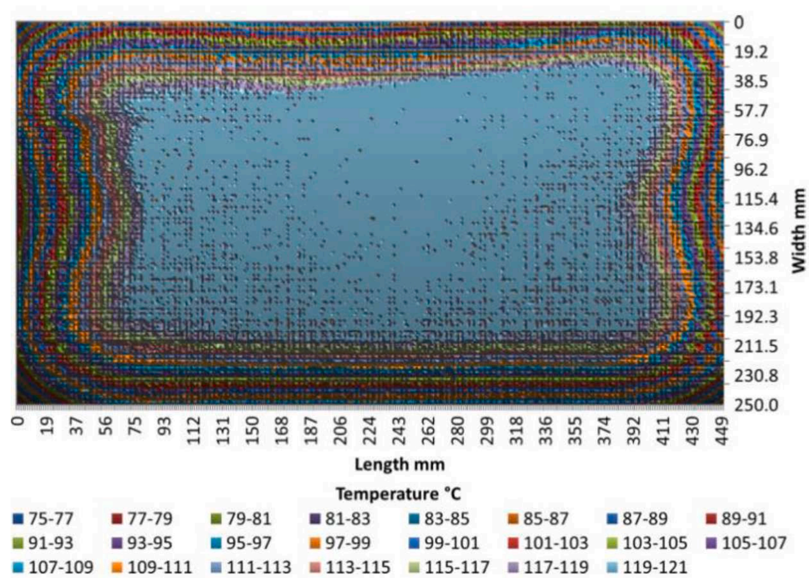

Fig. 8. Temperature distribution over a 450 × 250mm CFRP panel cured at 120°C [37]

consolidating the main curing area, whilst separating the 8 individual plies between copper blocks to reduce contact resistance, as seen in Fig. 7.

This experimental setup is impractical to repeat due to the complexity of applying electrodes to each ply and the cured sample size was comparatively small (60 mm x 30 mm). Tensile strain to break, and energy to break were higher than oven cured samples, 4.1% to 2.2% and 0.57 MJ^{-3} to 0.43 MJ^{-3}, respectively, suggesting the electrode setup could provide even heating and additional structural benefits to the composite.

Wellekotter and Bonten [83] investigated the effect of various electrical contact setups for the Joule heating of thermoplastic composites. A design of experiments (DOE) was completed, that found a larger contact area increased the performance of the heating process and part quality. Increasing contact force was also determined as a positive factor in the DOE, which is not possible without of autoclave methods, however, could be applied in specific cases, such as a mechanical press. Resistance welding of thermoplastic composites is more established and will have transferable methods to electric curing of composites [120], however, these are limited in scope and have moved towards metal mesh and nanocomposite heating elements providing better reproducibility and scaling [121].

2.2.3. *Evaluation against existing curing methods*

Y. Gu et al [38] investigated vacuum assisted resin infusion moulding heating methods, comparing oven, heated tooling, and internal resistive heating. Internal resistive heating provided the fastest heating rate (30°C/min), but also the highest temperature delta over the component (13°C) in comparison to heated tooling at 25°C/min with a 4°C difference and oven at 2°C/min and 0°C deltas. The importance of tooling materials was highlighted, and those manufactured with applicable thermal properties would assist in the temperature distribution of resistive heating. Athanasopoulos et al. [78] also compared electric cures in dry carbon infusion, pre-preg and oven samples, able to produce samples with the same DoC or more (±0.5%), and matching tensile properties. The tooling used was also specific for the process, being a thermally insulating glass fibre reinforced plastic (GFRP) on top of an aluminium plate, which assisted in the low temperature delta over the component.

Hayes et al. [37] investigated the effect of the geometry of the CFRP, the connector geometry and connector position on the heating homogeneity, the final mechanical properties and the cure percentage of the part. Flexural modulus and strength matched oven and autoclave samples, with the DoC between oven and autoclave at 97.2%. When applying current from edge to edge, the power requirement increased linearly to the distance between the connectors, whereas when increasing thickness by 2 plies, the average increase in power was 5%. This suggests that electric cure could be suited to highly energy efficient cures of thick ply composites.

Temperature distribution data over the panel was recorded, as seen in Fig. 8. It shows that when electrically curing a CFRP panel, most of the centre of the panel is at the desired cure temperature. The temperature

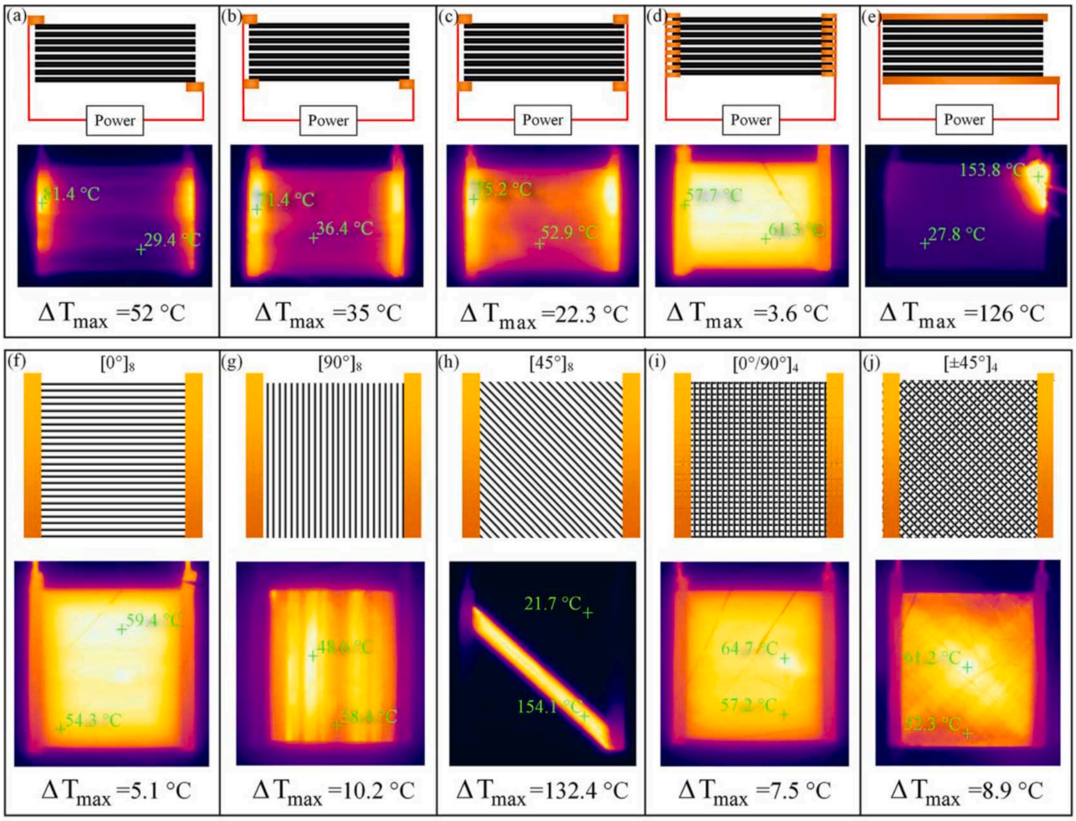

Fig. 9. Thermal images of different contact (a-e) and layup sequences (f-j) [14].

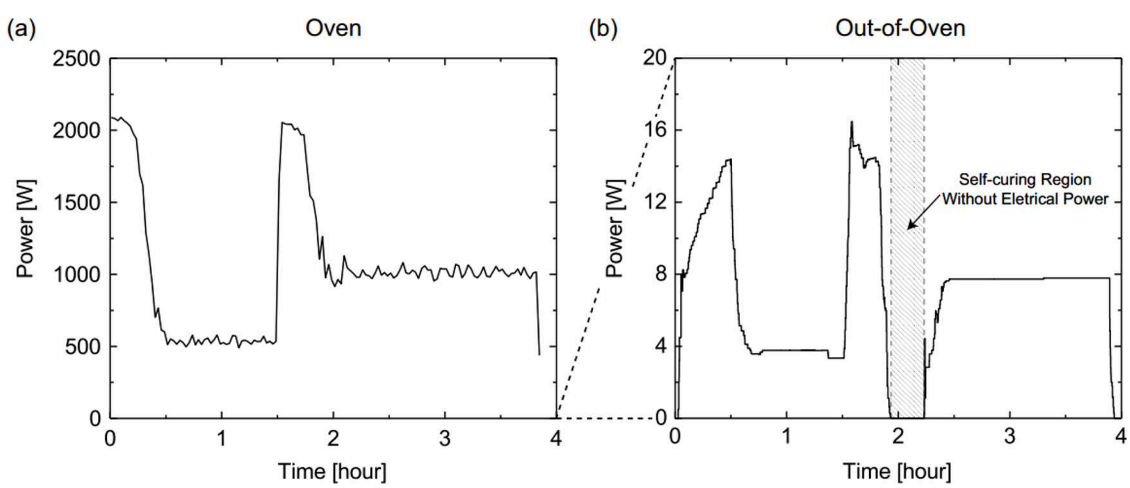

Fig. 10. Comparison of power consumption of a 160 ply (20 mm thick), 50 mm x 60 mm laminate via (a) oven curing and (b) direct electric curing. Note the differences in scale between the axes.[123]

starts to drop from around 20 mm from the edge, leading to around a 10°C reduction at the edges, which would lead to under cured areas.

Liu et al [14] investigated the electrical contact arrangements and positions, different fibre orientations and UD ply layups. Obtaining an even temperature distribution over the CFRP component is a crucial step in implementing this technology as a replacement for oven or autoclave. Edge to edge contact position within the ply layup was investigated (Fig. 9, a-e), and having the copper contacts placed between every ply reduced the contact resistance enough to not have a significant increase in temperature around these points.

Significantly the void content in the electrically cured components was consistently lower than the equivalent oven cured samples, as well as improved tensile strength and modulus. Comparisons were also made between different heating rates possible with this technology, namely 1, 3, 5, and 10°C/min, which showed if heated and therefore cured too quickly, the void content will increase significantly, as well as significant decreases in compressive strength.

2.2.4. Specific manufacturing applications

S.A. Sarles and D.J. Leo [81] investigated the possibility of using a continuous carbon tow to cure an inflatable structure, suitable for space applications. The cure temperature was consistent along the length (1.1°C root mean square), using thermocouples and a PI controller, which overcomes a significant challenge in joule heating of composites.

Optimised cure cycles were developed in this study, which achieved higher heating rates and shorter cure times, however, they did not consider the potential of uncontrolled exothermic reactions in thicker composites.

S.Liu et al [84] also developed a rapid composite repair system using the Joule effect to cure pre-preg patches onto CFRP components, removing the requirement for heated blankets. This had the advantage of being able to heat uniformly through the thickness of the patch, rather than conduction from the outer face of the component. The repair cure temperature was within ±5°C of the desired temperature, with void content being comparable to heater blanket repairs.

Robert et al [122] developed a novel towpregging line, using copper rollers as electrodes to Joule heat carbon tow to melt powder epoxy into the fibre. Power consumption was significantly lower than the equivalent IR lamp, whilst heating more uniformly. The resulting laminates manufactured matched or outperformed commercially available towpreg systems.

The sustainability of this method has been considered in more detail than other methods, as it is easier to monitor the power going directly into the cure, as it is commonly displayed using the power supplies used. Hayes et al detailed the effect of thickness and length increases on the power usage, which were both linear, with thickness having a lower impact on power usage than length. Jeonyoon Lee et al [79,123] directly compared a 160 ply, 50 mm x 60 mm panel cured in an oven and a joule heated CNT film which can be seen in Fig. 10.

This comparison is not completely representative, as it is heating a CNT film next to the component, and is deliberately a thick ply laminate, which appears to have exothermic runaway after the second ramp in the cure cycle, and exothermic results in no external power is required. C. Viney [75] noted the power requirement of the electric cure method compared to an oven was significantly reduced from 500 W maximum for an oven and 96 W for the electric cure method, with an 82% overall energy consumption reduction.

Joule effect curing has been shown to produce high quality composites at low cost, however, still has technical barriers to overcome to become widely adopted. The requirement of electrodes in a part means they have to be removed post cure, increasing costs, as well as the requirement of UD plies in the layup to obtain optimal temperature distribution. As mentioned in this section, there are some specific use cases where it very well suited such as patch repair, inflatable structures and low power curing. To be implemented more universally, the curing method needs to be more universally compatible with more composite types. This may be possible with future developments with CNT interleaves or joule effect heated tooling.

2.3. RF Curing

RF heating is similar to MW heating; however, it has a few key differences that have restricted widespread adoption in curing composites, of which there is little recent literature. A report by the Electric Power Research Institute considers RF heating for plastics processing and drying, although it does not mention it for CFRP manufacture [124]. This report also lists similar disadvantages to many EM cure methods:

- “Highly irregular shapes may heat non-uniformly in certain applications”
- “Certain products will not heat in a dielectric heating field”

Sweeney et al [49] focused on doping composites with multi-walled CNTs, mostly for joining processes rather than full-component curing. Lap-shear bonding of 0.25% CNT-epoxy resin was conducted at 44 MHz applying up to 100 W, achieving a shorter cycle time compared to oven cured samples. The CNT-epoxy composites were processed at 200°C and held at that temperature for two and three minutes. The samples were then loaded in shear per ASTM D1002 with the samples held at temperature for three minutes passing the testing.

Li and Dickie [90] bonded thermoset sheet moulding compound (SMC) and thermoplastic to steel sheet to produce lap shear coupons. The steel was used as the RF antenna, with the press head as the other electrode. Cycle time for the SMC was reduced from 20-30 minutes down to 20-30 seconds, with a high degree of crosslinking achieved, matching the bond strength achieved by using oven cure.

Vashisth et al [91] conducted a parametric study with various RF power levels and composite types. They trialled CF/epoxy (UD), CF/epoxy (plain weave) and CNT/epoxy composite materials at a variety of radio frequencies to determine which led to an increased rate of heating. Heating rates of 8°C/min were observed indicating the potential of RF heating. They also experimented with the RF power to observe how the heating rate was affected. As expected, the higher the power, the higher the subsequent heating rate. To validate the experimentation, they developed a COMSOL multi-physics model to evaluate the heating of CF/epoxy materials with RF power. The model showed good agreement in terms of heating rates with the physical experiments and future models will be used as a predictive tool.

2.4. Magnetic Induction

2.4.1. Background to magnetic induction heating

Electrically conductive materials can be heated when exposed to a magnetic field that is generated by an alternating current (AC) passing through a coil of wire –referred to as an induction coil, or inductor [125]. When applied to CFs, heating occurs primarily via resistive heating (from Joule losses) caused by the induced eddy currents [126]. This in turn can heat surrounding materials via conduction [93,94]. Junction heating and hysteresis loss have also been identified as potential heating mechanisms, particularly for ferromagnetic materials [95–97]. The effectiveness of the technique is directly related to the electrical properties of the material (which must form an electrically closed-loop, to allow the formation of eddy currents), the inductor coil design and the input power and current frequency [127].

The advantages of magnetic induction heating include the ability to rapidly transfer energy to a component, and the power input can be instantly adjusted as required to maintain or increase temperatures to match a programmed set point and can be a contactless heating method.

The heat generated by magnetic induction can be harnessed for various purposes as opposed to only curing, for example, a coil can be held in a fixed position or mounted to a robotic arm to allow for a continuous heating process, as is often seen with induction welding of thermoplastic composites. Typical applications have focused on the areas of thermoplastic forming and consolidation, fusion bonding, and rapid cure of adhesives [95,128]. In the case of heating CFRP components, magnetic induction can be used to directly heat the CFs. This requires the use of woven or non-crimp fabrics. UD material can be heated using magnetic induction when used in a quasi-isotropic layup sequence, so there are conductive pathways between fibres at each layer through thickness. A study by Khan et.al [129] showed that the heating response of a quasi-isotropic layup subjected to magnetic induction is more isotropic than if the plies were stacked in purely UD configuration which showed an anisotropic heating response. In both cases, it was shown that the fibres could be heated to 177°C which would allow the curing of most aerospace epoxies.

An alternative to directly heating the CF is to use an electrically closed loop susceptor, such as a metal mesh or conductive particles, placed at the location where heating is required. Heat is then transferred to the local area via conduction [98]. The technique is therefore versatile and can be used to deliver heat locally and through thickness without the challenges and drawbacks associated with methods such as ovens and autoclaves. Table 4 summarises some of the key studies covered in this review.

2.4.2. Magnetic induction for processing thermoset composites

The use of magnetic induction heating to cure a thermoset composite

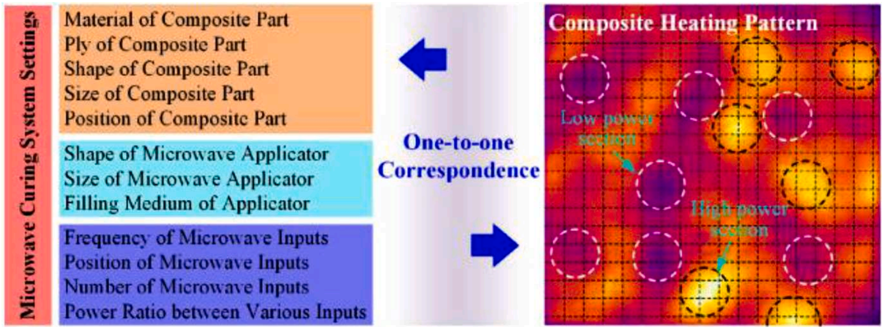

Fig. 11. Overview of MW curing system settings. IR image with highlighted hot/cold spots [36].

Table 2
Table summarising the key experimental studies and their outcomes covered in this review of MW processing of composites.

Author	Material	MW setup	Heating specifications	Significant outcomes
Kwak et al [57]	Gurit WE91-2 CFRP prepreg.	Vötsch Hephaistos MW.	10°C/min to 90, 100, 110 and 120°C dwells.	Industrial MW designed for composites. 10% increase in tensile strength.
Xuehong et al [60]	Bismaleimide (BMI) UD T700 CF, 170 × 90 mm, 22 plies.	WZD1S-03 Nanjing Sanle MW Technology Development Co.	Power based cured cycles, up to 220°C.	63 % reduction in cycle times, comparable void, and interlaminar shear stress (ILSS) to autoclave, slight reductions in flexural and fibre volume fraction.
Xuehong et al [61]	UD epoxy prepreg, T800 CFs, 175 × 90 mm, 14 plies	WZD1S-03 Nanjing Sanle MW Technology Development Co	Power based cured cycles, up to 220°C.	39 % reduction in cycle time, 22 % increase in compression strength, despire increased porosity. Evidence of increased interfacial adhesion of fibre to resin.
Li et al [64]	BMI UD CF, 100 × 100 mm, 1.5 mm thickness.	Custom design by Nanjing University. Fibre Bragg Gratings (FBG) used for strain monitoring.	1.5°C/min up to 200°C.	95% reduction in residual cure-induced strain, 64 % reduction in cycle time. Lower spring back in L-shaped components, by up to 1.2 °.
Lee and Springer[53]	Hercules AS/3501-6 carbon and Fiberite S2/9134B glass prepregs, 203 × 203 mm, 32 plies.	Commercial 700 W MW oven.	177°C, ramp rate not specified.	90 % reduction in gel time. Agreement between modelling and experimental.
Papargyris et al [62]	Araldite LY5052/HY5052 epoxy, satin weave T300 CFs, 200 × 300 × 3 mm.	Custom MW resin transfer moulding (RTM) setup, variable frequency, up to 250 W.	100°C cure.	50 % cycle time reduction. Equal flexural strength and void content, 9 % higher ILSS compared to oven cured RTM.
Thostenson and Chou [65]	E glass, Epon 862/ Epi-Cure W epoxy resin, 44 plies.	6 kW of MW power at 2.45 Ghz.	5°C/min up to 165°C.	Reduction in processing time, inside out MW processing reduced matrix cracking compared to autoclave cured samples.
Nuhiji et al [15]	Cycom 5320-1 T650 plain weave prepreg, 190 × 190 mm, 8 plies.	Vötsch HEPHAISTOS VHM 180/200.	3°C/min up to 177°C, manufacturers recommended cure cycle.	Investigated alternate tooling materials for MW cure, CFRP tooling performed best.
Green et al [31]	Cycom 5320-1 T650 plain weave prepreg, 200 × 200 mm, 1.5 mm thick.	Modified domestic MW, Panasonic NN-CF778.	3°C/min up to 177°C, manufacturers recommended cure cycle.	Conversion of domestic MW to cure composites with accurate multiphysics modelling.
Kwak et al [56]	Gurit Sparpreg UD CFs, 300 × 300 mm, up to 60 mm thick.	Vötsch Hephaistos MW 100/100 system.	2°C/min up to 120°C, manufacturers recommended cure cycle.	Highlights if the process setup is correct then high quality laminates can be manufactured. Practical method for MW penetration depth demonstrated.
Nuhiji et al [67]	Cycom 5320-1 T650 plain weave prepreg, 600 × 600 mm, 14 plies.	Vötsch HEPHAISTOS VHM 180/200.	3°C/min up to 177°C, manufacturers recommended cure cycle.	Multiphysics model of MW field, showing effect of frequency on field homogeneity and temperature distribution, experimentally validated.
Feher and Thumm [68]	LY556 infusion resin, CF plain weave, up to 450 × 300 mm.	DLR custom HEPHAISTOS-SA/CA.	20°C/min up to 130°C.	Details the process on developing industrial MW system suitable for composite processing at pressure.
Zhou et al [36]	Short fibre CFRP composite (T300 fibres), 200 × 200 × 2 mm	Custom design by Nanjing University, 2.45 GHz, 20 KW.	3°C/min up to 120°C. Active temperature compensation through selective magnetron activation.	Significant reduction in temperature difference (<10°C) over the panel, a 67 % improvement over single pattern and 58 % improvement over random pattern heating modes. Methodology can be transferred to other heating technologies.
Zhou et al [107]	UD CFRP, epoxy matrix, T800 fibres. 300 × 300 × 2 mm. Copper/polyaimide resonance structure-insulator (RSI) films.	Custom design by Nanjing University, multimode, high pressure, 2.45 GHz.	CFRP uniformly up to 120°C at 1 and 5°C/min.	CFRP/RSI film enabled high MW absorption and heating of CFRP to cure temperature. Less than 10°C range of temperature over the panel.
Zhou et al [108]	UD CFRP, epoxy matrix, T800 fibres. 600 × 300 × 2 mm. Copper/polyaimide RSI films.	Custom design by Nanjing University, multimode, high pressure, 2.45 GHz at 1500 W and 915 MHz at 1000 W.	Multi zone heating of CFRP uniformly up to 120°C.	Able to independently zonally heat CFRP with multimode RSI films. Allows for MW curing of components with non-uniform thickness.

Table 3
A summary of studies on the direct electric curing method, overviewing the materials used, electrode configuration, heating performance and significant outcomes

Author	Material	Electrode configuration	Heating specifications	Significant outcomes
Chien et al. [80]	Carbon nanotube (CNT) modified PAN fibres	Electrodes clamped at tow ends	1000°C on 2 mm fibres 300°C on 76 mm fibres at low current, 0-6 mA	Conductivity increase with temperature CNT doped PAN fibres
Naskar and Edie [77]	Pitch (2K) and PAN (12K) based fibre tows Ultem® powder (polyetherimide)	Silver paste and copper wires	0-400°C within 50 seconds, 150 mm tows	Conductivity increase with temperature Successful rigidisation, however, flaws in final composites
S.A. Sarles & D.J. Leo [81]	U-Nyte epoxy coated tow	Crocodile clips	Up to 200°C following the cure cycle. 50°C/min ramp rate.	Proving the technology for alternate curing situations such as inflatable space structures
H Fukuda [76]	Torayca P3060 pre-preg	Aluminium foil. Edge to edge & through the thickness (Fig. 6)	Proportional integral derivative (PID) control to cure cycle. Up to 180°C.	Electrode layouts reviewed. Power reduction observed.
C. Joseph [75]	Hexcel 914c pre-preg Unidirectional	Copper blocks on each ply, edge to edge (Fig. 7)	Followed cure cycle up to 175°C	Increased mechanical properties. Power reduction.
Y. Gu et al. [38]	T700SC unidirectional (UD) Carbon, DGEBA E51 resin	Copper foil, stacked between plies	Followed cure cycle up to 120°C, 30°C/min ramp rate. 13°C Δ over panel.	Dry fibre infusion experimental process. Rapid heating rates, however poor temperature distribution. Highlighted issues with tooling.
N. Athanasopoulos et al (2008) [78]	CF preform/Epocast52 epoxy, UD sigrafil E022 pre-preg	Copper electrodes	Followed cure cycle, up to 130°C	Matching mechanical properties to oven cured. Comparison between pre-preg and infusion samples. Accurate power data
S. Hayes et al. [37]	Cycom 950-1 plain weave pre-preg	Copper foil or Copper/ flexible printed circuit board (PCB)	Followed cure cycle, up to 160°C	Understanding of scalability and practical implementation. Highlighting temperature distribution issues.
S. Liu et al [14]	UIN10000/T800 UD pre-preg	Copper strips, 10mm wide	Followed cure cycle, up to 120°C	Detailed experimental procedure, layup/electrode arrangement on temperature distribution, mechanical properties comparison.
Reese et al.[82]	Recycled carbon, Nylon 6, custom weave	Press plates as electrodes, 900-2500mm^2. Through thickness.	222°C (T^{melt}) within 15 seconds	Combination of press and joule heating to reduce cycle time

component, through heating the CFs or an embedded susceptor, is limited. Investigations of induction curing through heating the fibres, have only been proven on lab scale components at TRL 3 or lower. Pitchumani and Johnson used induction to heat a composite preform [99] to control the flow of epoxy resin in a VARTM process. A woven fibreglass mat was used with a layer of woven CF embedded in the preform to act as the susceptor, eliminating the need for metallic inclusions and reducing weight and corrosion concerns. The inductor coil is moved as determined by the active control program to facilitate resin flow and preform fill. The induction system was not used to facilitate the final cure of the component; however, directly heating the fibres to induce volumetric cure would require a coil that was at least as large as the part to be cured.

2.4.3. Magnetic induction for processing thermoplastics

The use of magnetic induction heating for the processing of thermoplastics has been focused on thermoforming and fusion bonding processes, driven by the advantages of the technique that include rapid processing times, low energy consumption and the ability to volumetrically heat a substrate or tool.

The heating of thermoplastics for thermoforming processes can be completed without conductive fillers [128] if part of the component is electrically conductive or indirectly by heating a metallic tool or forming plates. In the Induction Diaphragm Forming (IFD) process, thermoplastic sheets are held between two sheets of aluminium. The aluminium is heated by induction that then heats the thermoplastic via conduction, with the molten stack then formed over a die.

Ramulu et al. [103] performed a comparison of autoclave and induction joining for processing CF/ PEEK, CF/PIXA-M [130] and Hybrid Titanium Composite Laminates (HTCL) panels. Induction heating presents a potential processing solution to autoclave, enabling rapid heating and reducing cycle time and costs. Micrographs showed CF/PEEK panels consolidated using induction heating and autoclave both showed high quality laminates. Induction processed CF/PIXA-M panel showed increased levels of void formation and fibre distortion, and the HTCL panel showed poor quality consolidation compared to autoclave processing.

Rudolf et al [94] investigated the effect of various induction heating process parameters on the temperature distribution and heating rate for Polyphenylene Sulfide (PPS) and Polyamide (PA) reinforced CF composite. There was a direct correlation between heating rate and coil separation distance, with a quadratic growth associated with increased separation. The authors also found that heating time is reduced by increasing the input power and that heat generation was found to be driven by Joule losses.

2.4.4. Magnetic induction for curing adhesives

Magnetic induction technology has been investigated to cure adhesives, in the context of in-situ repairs or rapid joint formation with reduced cycle times. For applications involving GFRP composites, adhesive curing via induction is only possible with the use of a susceptor. Tay et al. [98] investigated the accelerated curing of room temperature paste adhesive bonded GFRP single lap-shear (SLS) specimens, with and without a copper mesh susceptor in the bond line. The magnetic induction heating was successful, with shear strength results comparable to, or better than, oven cured specimens. Mahdi et. al. [97] performed a similar investigation using a stainless-steel mesh and comparing two different types of epoxy paste adhesive. It was found that the shear strengths of the induction cured specimens were within 10 % of the results obtained when oven cured. Severijns et. al. [93] used varying levels of iron particles as a susceptor for curing adhesive in GFRP SLS samples. Samples, where the adhesive was induction, cured had up to 6 % higher shear strengths than their oven counterparts that also had iron filled bond lines. The introduction of iron particles reduced the shear strength of all samples, compared to the unmodified adhesive samples, as well as adding weight to the assembly.

Studies have been carried out to investigate whether heating CFRP adherends directly, without a susceptor, could cure adhesive bond lines via conductive heat transfer. Frauenhofer et. al. [100] investigated woven and UD CF architectures and how that influenced heating rates on CFRP-to-CFRP and CFRP-to-Aluminium SLS components. Lower frequencies resulted in more homogeneous heating than higher frequencies, and rapid curing via magnetic induction led to better bulk adhesive properties and DoC compared with samples cured with longer

Table 4
Summary of key studies of induction heating of composites for curing and adhesive curing.

Author	Material	Experimental setup	Processing specification	Significant outcomes
Pitchumani and Johnson [99]	Woven CF mat, 305 × 305 mm (BFG Industries), Epon 815C epoxy resin.	32 × 68 mm coil size, mounted to motion stage for active RTM.	Not directly observed. Feedback control based off flow front.	Localised heating for active flow front control of vacuum assisted resin transfer moulding (VARTM).
Ramulu et al [103]	Polyether ether ketone (PEEK), PIXA-M, Hybrid titanium composite laminate.	Comparison of induction and autoclave processing of thermoplastic laminates.	Forced cooling on the induction samples. No data on temperature.	Less than 10% difference in in flexural and tensile properties. Significantly quicker processing time.
Rudolf et al [94]	Process parameter setup on CF-PPS, 2mm thick, laminate structure tests on CF polyamide 66.	Understanding coil setup parameters on heating performance. Continuous induction welding process.	Investigated different coil geometries, frequency, power, distance from laminate.	Heat only generated in closed fibre loops, i.e UD fibres. Maximum temperature is limited by power. Through thickness temperature distribution is even.
Tay et al [98]	Hysol EA9394 epoxy paste adhesive, GFRP substrate, 34 plies, 3 mm.	Curing of paste adhesive for composite repair to reduce cycle time, tested with single lap shears.	Copper susceptor introduced in adhesive.	Copper susceptor reduced strength slightly, but reduced scatter of data. Reduced cycle time from 120 hrs to 15 minutes.
Severijns et al [93]	EC9323 epoxy paste adhesive, GFRP substrates, 8 plies.	One-turn and pancake coils tested. Tested with single lap shear bonding.	Iron particles introduced into adhesive as susceptor. Varying process parameters for heating performance.	Iron particles reduced shear strength by 15-20 % in all samples, but induction cured samples were 6 % higher than oven cured samples.
Frauenhofer et al [100]	HexPly 913 CF-epoxy laminates, UD and woven. Henkel Loctite EA 9394 adhesive.	Testing consolidation of laminates and subsequent ILSS and flexural strength. SLS test of adhesive bonded parts.	Varying frequencies tested to determine heating performance, 120°C cure.	Penetration depth higher than metals. Able to heat both side of SLS and cure adhesive effectively.
Sánchez Cebrián et al [101]	Huntsman ME 10049-4/LMB 6687-2 epoxy adhesive, Cytec MTM 44-1 CFRP.	2 part heating method to reduce volatiles and voids being created.	Stepped cure cycle, up to 140-180°C, at 25°C/min.	Cure time reduced from 4 h to 30 min without increase in void content.
Kim et al [102]	3M F-163-2 K adhesive film, AL-6061-T6 aluminium.	Carbon patched double lap aluminium joints for use in repairs. Compared oven and induction.	120°C for 90 minutes for direct comparison to oven cured samples.	Induction samples matched oven cured samples bond strength.

cycle times using an oven. Higher shear strength values were obtained in all cases where the adhesive was cured via induction, compared to the oven baseline. This proved the possibility of heating the composite to conductively cure the adhesive and could do so from one side and rapidly.

Cebrián et al. [101] used magnetic induction to heat CFRP laminates to cure adhesive via conduction alongside a model simulating and predicting the DoC. The model was validated using SLS specimens that were monitored for temperature and DoC, and the results showed a good correlation between predictive and actual values.

Kim et. al. [102] investigated CFRP patch repairs of aluminium double lap-shear joints using either oven cure or induction heating. Two types of patches, bonded to the aluminium via a single layer of film adhesive, were investigated: pre-cured and co-cured UD composite. Additional samples were prepared with 0.5 %wt. CNTs in a resin mix was applied to the bonding surfaces before adhesive application. The authors found that the co-curing of CFRP patches and film adhesive yielded higher shear strengths than bonding with pre-cured patches. No difference in shear strength was found between the oven and induction heating when bonding pre-cured patches, although oven co-curing presented 8% higher shear strengths compared to induction co-cured. The inclusion of CNTs at the bond interface increased shear strengths in all cases. For patch repair applications, this is advantageous because it would remove the need for IR heaters, heated blankets/mats, or transferring large sections to an autoclave or oven to complete the repair – provided a means of applying sufficient consolidation was implemented. This saves on process time, energy, floor space and storage requirements. There is a need for further research to validate the technique on larger components and to develop the process.

3. Future challenges

The research presented shows some of the challenges and solutions to a range of EM curing methods, however in the following section are three main themes that have occurred frequently and will need further research as the methods become more industrially relevant and frequent in use.

3.1. Sustainability and economics of novel curing methods

One of the most significant benefits of many of these novel cure methods is the low energy consumption when compared to oven or autoclave methods. This is due to the direct heating nature of these techniques described in Fig. 1, meaning that the energy going into the curing system is only heating the component. The cost has always been a strong driver in any manufacturing situation, however with sustainability now reaching similar importance, it is expected that the energy consumption is given more scrutiny. Reduction in energy usage will lead to lower costs of a process as well as improve the sustainability of existing processes, particularly in aerospace where changes to materials and processes can take years due to the high cost of qualification.

Sustainability as a topic has increased in prevalence around the pandemic, which has meant that the overall sustainability as a benefit is not discussed in detail in papers reviewed before this date. The primary focus of the papers has been the resulting composite mechanical properties, with authors assuming or not accounting for sustainability or being cost effective at the lab scale. Another issue that is considered in few cases is the effects of scaling up will have on not only the composite mechanical properties but on the economic practicality of it for composite manufacturers.

3.2. Control systems

An aspect of novel curing methods is the control systems that accompany them. Closed loop PID control algorithms have traditionally controlled oven, autoclave and press plattern temperatures. These controllers are suitable when longer time intervals are used and when temperature overshoots need to be avoided. When ramp rates in cure cycles increase from 2-3°C/minute to 10-20°C/minute, closed loop PID controllers would have to be tuned accordingly to optimise for each component [131]. These controllers are commonly Single Input Single Output (SISO) or Multiple Input Single Output (MISO) and are unsuitable for accommodating the uneven heating of a variety of cure methods or controlling heating in multiple and specific areas, which require more complex Multiple Input Multiple Output (MIMO) controllers [31].

There is an opportunity to use enhanced temperature and cure monitoring tools alongside these cure methods, as well as predictive cure models that can account for the highly controllable power inputs [85].

Non-conventional heating methods provide a new challenge to heating controllers to overcome some of the disadvantages, particularly localised or uneven heating patterns. Rapid heating would require updated or faster controllers, alongside predictive cure which could allow for more consistent quality cures. Because of these reasons, increased monitoring of the cure is required, which can increase setup cost, however, a key trend of Industry 4.0 is data collection [132,133], suggesting existing manufacturing methods will require this level of data collection in the future.

MIMO control systems have been suggested as a solution to ensure even bulk heating of large composites, regardless of geometry [31]. These difficult control system problems are complex to implement, therefore systems based on pattern detection and understanding of the underlying physics have been developed. Zhou et al [36] developed a real-time thermal imaging monitoring system to improve the MW curing process. A database of heating patterns from different magnetron activations and therefore different standing waves are recorded in a database. The composite is heated, and the heating pattern is fed back to the control system which calls on the database for an inverse pattern and alters control parameters to homogenise the heat pattern. The controller can adjust which magnetrons are activated, the frequency of the MW inputs and the power ratio Fig. 11.

Pitchumani and Johnson [99] developed an active controller that moved an induction coil to the position in an X-Y plane of a composite to assist in heating resin to reduce viscosity and ensure there was an even flow front during the VARTM process. A method like this could be applied to local MW, induction, or IR transmitters to cure components locally.

D. Kim et al. [111] produced a cure kinetic model of out-of-autoclave prepreg to control the cure of the prepreg at different lengths of outlife with high accuracy, however, stated that the model could be used to gain further efficiencies from existing manufacturing processes.

3.3. Matrix modification for enhanced susceptibility

Modifying polymers with fillers to improve material properties is a practice that has existed for decades, one of the most common examples being carbon black in tyre rubber to increase wear resistance [134]. More recently research has focused dispersion of graphene or carbon nanotubes in matrices, which enhances a variety of properties, including fracture toughness and tuning of electrical conductivity [135], which affects the susceptibility of many of the curing methods mentioned in this paper.

Conductive resins, and therefore composites can increase the effectiveness of novel curing methods [136] which commonly heavily rely on conductive fibres. Nanocomposites without reinforcing fibres have been cured using MWs [73,74], RF [49], direct electric [80,86–88] and induction [102] successfully.

An electrically conductive matrix in a CFRP composite would be more isotopically electrically conductive, therefore potentially more isotropic heating within novel curing methods. Mas et al [89] highlighted three examples of how CNT loaded epoxy could be used with electric cure, for composite fabrication, composite repair, and as electronic adhesive/solder. In all situations, it was possible to cure the epoxy, without the requirement of CFs as a conducting element.

3.4. Modelling of heating methods

Modelling of curing is vital for the acceleration of development of these methods, as experimentation is time consuming and costly. The majority of the methods mentioned require multi-physics modelling to provide effective and accurate results and due to the low TRL of this area of research, it is more accessible to do so on these less complex systems. Tertrais et al [137,138] have published initial modelling of a Vötsch MW cavity. The publications detailed the mathematical equation necessary to calculate in-plane and out-of-plane thermo-chemical analysis but included no results.

Kim et al [139] successfully modelled the representative volume element of an electrically cured chopped strand CF composite, characterising the heating behaviour dependent on fibre volume fraction.

Nuhiji et al [67] successfully modelled and simulated an industrial scale MW using COMSOL Multiphysics. A quarter-scale model of the Votsch MW system was generated and a parametric study of heating a composite panel using a variety of frequencies and magnetron configurations. The analysis showed that as frequency increased from 500 MHz to 2.45 GHz, the heat distribution within the panel became less homogeneous. The authors' findings indicated that by altering the frequency or the number of magnetrons, the heat distribution changed. This could then be used to inform future control algorithms to improve the composite curing process.

Mitschang and Neitzel [140] used a predictive Finite Element model to generate parameters for use in a Continuous Induction Welding (CIW) process. The model aimed to reduce the quantity of physical testing required to validate the process parameters, reducing overall effort, time, and costs. The outputs were validated using a limited set of single-lap welded panels, using PPS reinforced with either plain weave or 5-Harness Satin.

4. Conclusion

Existing composite curing methods produce consistently high-quality components; however, this is one of their few advantages. The research covered in this paper shows that novel curing methods can produce equivalently high, or higher quality composites, and using considerably less energy. Depending on the method used there are also other significant advantages apart from the component quality, for example, increased heating rates, safer operation in thicker layups, and lower capital expenditure equipment.

The low TRL of these curing methods means that the expertise, equipment, and time required to produce components of the same quality as existing methods are not feasible currently. As these methods are developed, standardisation will follow, allowing further research at higher TRLs and implementation in components in small specific cases.

After the review of a wide range of novel curing methods, it is expected that the themes of future research in these areas will be:

- Environmental impact: One of the most significant benefits of these novel cure methods is their energy efficiency compared to standard cure methods, however, this is explored in very little detail by most of the papers reviewed. As more scrutiny is put on the energy efficiency of the composite supply chain,
- Modelling of the novel cure methods: A Complex multiphysics methodology is required and has not been explored for many curing scenarios. For example, it has been investigated in detail for MW curing, however very little for electric cure.
- Industrialisation and compatibility with existing methods: A lot of the research covered rarely considers how the process will work in industry, or how this transition can be made. This is expected in with low TRL research, however as these cure methods are developed, industrialisation needs to be considered in more detail.
- Characterisation on component level: Significant research has been completed on the thermal and mechanical characterisation of components manufactured using novel cure methods, which allows for easy comparison to existing cure methods. The next step for these comparisons is the component level comparisons, including the practicality and capital expenditure over a production series of a component.

Research needs to continue in these areas to overcome these challenges to ensure the benefits start to outweigh the issues that still occur. Once these are solved, they can start to be tested in service and data collected with prolonged use, which will help wider adoption in high value industries such as automotive or aerospace. These future curing methods can solve the future requirements of these industries for quality and quantity, as well as meeting future energy saving requirements.

Funding sources

Funding: This work was supported by the European Union's Horizon 2020 research programme under grant agreement No 760940, under the project titled MASTRO.

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.

References

[1] PE Irving, C Soutis, Polymer Composites in the Aerospace Industry, Elsevier, 2020, https://doi.org/10.1016/c2017-0-03502-4.
[2] ICAO. 2. What is CORSIA and how does it work? 2020. https://www.icao.int/environmental-protection/Pages/A39_CORSIA_FAQ2.aspx (accessed September 11, 2020).
[3] JR Duflou, J de Moor, I Verpoest, W. Dewulf, Environmental impact analysis of composite use in car manufacturing, CIRP Ann. - Manuf. Technol. 58 (2009) 9–12, https://doi.org/10.1016/j.cirp.2009.03.077.
[4] Aerospace Technology Institute, Composites UK. Composite material applications in Aerospace, Insight, ATI, 2018.https://www.ati.org.uk/wp-content/uploads/2021/08/insight_9-composites_amended-2018-09-20.pdf (accessed December 21, 2021)
[5] T Ishikawa, K Amaoka, Y Masubuchi, T Yamamoto, A Yamanaka, M Arai, et al., Overview of automotive structural composites technology developments in Japan, Compos. Sci. Technol. 155 (2018) 221–246, https://doi.org/10.1016/j.compscitech.2017.09.015.
[6] YS Song, JR Youn, TG. Gutowski, Life cycle energy analysis of fiber-reinforced composites, Compos. Part A: Appl. Sci. Manuf. 40 (2009) 1257–1265, https://doi.org/10.1016/j.compositesa.2009.05.020.
[7] Liddell HPH, Brueske SB, Carpenter AC, Cresko JW. Manufacturing energy intensity and opportunity analysis for fiber-reinforced polymer composites and other lightweight materials. Proceedings of the American Society for Composites - 31st Technical Conference, ASC 2016, 2016.
[8] Marino M, Sabatini R. Advanced lightweight aircraft design configurations for green operations, 2014. 10.13140/2.1.4231.8405.
[9] Timmis AJ, Hodzic A, Koh L, Bonner M, Soutis C, Schäfer AW, et al. Environmental impact assessment of aviation emission reduction through the implementation of composite materials n.d. 10.1007/s11367-014-0824-0.
[10] JR Duflou, J De Moor, I Verpoest, W. Dewulf, Environmental impact analysis of composite use in car manufacturing, CIRP Ann. Manuf. Technol. 58 (2009) 9–12, https://doi.org/10.1016/j.cirp.2009.03.077.
[11] D Abliz, Y Duan, L Steuernagel, L Xie, D Li, G. Ziegmann, Curing methods for advanced polymer composites - a review, Polym. Polym. Compos. 21 (2013) 341–348, https://doi.org/10.1177/096739111302100602.
[12] SL Agius, KJC Magniez, BL. Fox, Cure behaviour and void development within rapidly cured out-of-autoclave composites, Compos. Part B: Eng. 47 (2013) 230–237, https://doi.org/10.1016/j.compositesb.2012.11.020.
[13] DA Lakho, D Yao, K Cho, M Ishaq, Y. Wang, Study of the curing kinetics toward development of fast-curing epoxy resins, Polym. Plastics Technol. Eng. 56 (2017) 161–170, https://doi.org/10.1080/03602559.2016.1185623.
[14] S Liu, Y Li, Y Shen, Y. Lu, Mechanical performance of carbon fiber/epoxy composites cured by self-resistance electric heating method, Int. J. Adv. Manuf. Technol. (2019), https://doi.org/10.1007/s00170-019-03707-0.
[15] B Nuhiji, T J Swait, MP Bower, JE Green, RJ Day, RJ. Scaife, Tooling materials compatible with carbon fibre composites in a microwave environment, Compos. Part B: Eng. (2019), https://doi.org/10.1016/j.compositesb.2019.01.047.
[16] CO Mgbemena, D Li, MF Lin, PD Liddel, KB Katnam, VT Kumar, et al., Accelerated microwave curing of fibre-reinforced thermoset polymer composites for structural applications: A review of scientific challenges, Compos. Part A: Appl. Sci. Manuf. 115 (2018) 88–103, https://doi.org/10.1016/j.compositesa.2018.09.012.
[17] M. Héder, From NASA to EU: the evolution of the TRL scale in public sector innovation, The Innovation J.: The Public Sector Innovation J. n.d 22 (2017) 3.
[18] T Centea, LK Grunenfelder, SR. Nutt, A review of out-of-autoclave prepregs - Material properties, process phenomena, and manufacturing considerations, Compos. Part A: Appl. Sci. Manuf. 70 (2015) 132–154, https://doi.org/10.1016/j.compositesa.2014.09.029.
[19] C Hull, TW. Clyne, An Introduction to Composite Materials, 2nd ed., Cambridge University Press, Cambridge, 1996.
[20] B Ellis, WR Ashcroft, SJ Shaw, WJ Cantwell, HH Kausch, GP Johari, et al., Chemistry of Epoxy Resins, Springer-Sci.+Bus. Media, B.V. (1993).
[21] Huntsman, High Performance Components Selector Guide n.d (2018).
[22] HT. Hahn, Residual stresses in polymer matrix composite laminates, J. Compos. Mater. 10 (1976) 266–278, https://doi.org/10.1177/002199837601000401.
[23] TE Twardowski, SE Lin, PH. Geil, Curing in thick composite laminates: experiment and simulation, J. Compos. Mater. 27 (1991) 216–250, https://doi.org/10.1177/002199839302700301.
[24] TA Bogetti, JW. Gillespie, Process-induced stress and deformation in thick-section thermoset composite laminates, Jo. Compos. Mater. 26 (2016) 626–660, https://doi.org/10.1177/002199839202600502.
[25] G Struzziero, JJE. Teuwen, Effect of convection coefficient and thickness on optimal cure cycles for the manufacturing of wind turbine components using VARTM, Compos. Part A: Appl. Sci. Manuf. 123 (2019) 25–36, https://doi.org/10.1016/j.compositesa.2019.04.024.
[26] A. P. Mouritz AGG. Health Hazards of Composites in Fire. Fire Properties of Polymer Composite Materials, Springer Netherlands; 2007, p. 359–84. 10.1007/978-1-4020-5356-6_12.
[27] ZL. Yang, Optimized curing of thick section composite laminates, Mater. Manuf. Processes 16 (2001) 541–560, https://doi.org/10.1081/AMP-100108526.
[28] Young W bin, Compacting pressure and cure cycle for processing of thick composite laminates, Compos. Sci. Technol. 54 (1995) 299–306, https://doi.org/10.1016/0266-3538(95)00067-4.
[29] N Slesinger, T Shimizu, ARA Arafath, A. Poursartip, Heat transfer coefficient distribution inside an autoclave, ICCM17 Edinburgh (2017).
[30] L Nele, A Caggiano, R. Teti, Autoclave cycle optimization for high performance composite parts manufacturing, Procedia CIRP 57 (2016), https://doi.org/10.1016/j.procir.2016.11.042, 241–6.
[31] Green JE, Nuhiji B, Zivtins K, Bower MP, Grainger R v., Day RJ, et al. Internal model control of a domestic microwave for carbon composite curing. IEEE Trans. Microwave Theory and Techniques 2017;65:4335–46. 10.1109/TMTT.2017.2693145.
[32] S Enoki, K Iwamoto, R Harada, K Tanaka, T. Katayama, Heating properties of carbon fibers by using direct resistance heating, WIT Trans. The Built Environ. n.d (2012) 124, 10.2495/HPSM120211.
[33] Y Li, X Hang, N Li, X. Hao, A temperature distribution prediction model of carbon fiber reinforced composites during microwave cure, J. Mater. Processing Technol. 230 (2015), https://doi.org/10.1016/j.jmatprotec.2015.12.001, 280–7.
[34] Y Li, N Li, J. Gao, Tooling design and microwave curing technologies for the manufacturing of fiber-reinforced polymer composites in aerospace applications, The Int. J. Adv. Manuf. Technol. 70 (2014) 591–606, https://doi.org/10.1007/s00170-013-5268-3.
[35] N Li, Y Li, X Wu, X. Hao, Tool-part interaction in composites microwave curing: Experimental investigation and analysis, J. Compos. Mater. 51 (2017), https://doi.org/10.1177/0021998317693674, 3719–30.
[36] J Zhou, Y Li, N Li, S Liu, L Cheng, S Sui, et al., A multi-pattern compensation method to ensure even temperature in composite materials during microwave curing process, Compos. Part A: Appl. Sci. Manuf. (2018), 107:10–20. 10.1016/j.compositesa.2017.12.017.
[37] SA Hayes, AD Lafferty, G Altinkurt, PR Wilson, M Collinson, P. Duchene, Direct electrical cure of carbon fiber composites, Adv. Manuf.: Polym. Compos. Sci. 1 (2015) 112–119, https://doi.org/10.1179/2055035915Y.0000000001.

[38] Y Gu, X Qin, M Li, K Zhang, Z. Zhang, Temperature distribution and curing behaviour of carbon fibre/epoxy composite during vacuum assisted resin infusion moulding using rapid heating methods, Polym. Polym. Compos. 23 (2015) 11–20, https://doi.org/10.1177/096739111502300102.
[39] PK Bajpai, I. Singh, Reinforced Polymer Composites, 1st ed., Wiley-VCH, 2020.
[40] I Zhilyaev, C Brauner, S Queloz, H Jordi, R Lüscher, S Conti, et al., Controlled curing of thermoset composite components using infrared radiation and mathematical modelling, Compos. Structures (2021) 259, https://doi.org/10.1016/j.compstruct.2020.113224.
[41] M Uday, P. Kirankumar, Heat transfer studies for infrared radiation assisted curing in polymer composites, J. Phys.: Conference Series 1473 (2020), https://doi.org/10.1088/1742-6596/1473/1/012027. Institute of Physics Publishing12027.
[42] R Weber, C Freitag, T v. Kononenko, M Hafner, V Onuseit, P Berger, et al., Short-pulse laser processing of CFRP, Phys.Procedia 39 (2012) 137–146, https://doi.org/10.1016/j.phpro.2012.10.023. Elsevier B.V.
[43] P Monnot, D Williams, M. di Francesco, Power Control of a Flashlamp-Based Heating Solution For Automated Dry Fibre Placement, 18, ECCM, Athens, 2018, 24–8.
[44] S.T. Peters, Composite Filament Winding, ASM International, 2011.
[45] A. Endruweit, M.S Johnson, ACL, Curing of Composite Components by Ultraviolet Radiation: A Review, Polym. Compos. 27 (2006) 119–128, https://doi.org/10.1002/pc.
[46] ID Robertson, M Yourdkhani, PJ Centellas, J En Aw, DG Ivanoff, E Goli, et al., Rapid energy-efficient manufacturing of polymers and composites via frontal polymerization, Nature 557 (2018), https://doi.org/10.1038/s41586-018-0054-x, 223–7.
[47] E Goli, SR Peterson, PH. Geubelle, Instabilities driven by frontal polymerization in thermosetting polymers and composites, Compos. Part B: Eng. 199 (2020), 108306, https://doi.org/10.1016/j.compositesb.2020.108306.
[48] AC Metaxas, RJ. Meredith, Industrial microwave heating, IET (1988), https://doi.org/10.1049/pbpo004e.
[49] CB Sweeney, AG Moran, JT Gruener, AM Strasser, MJ Pospisil, MA Saed, et al., Radio frequency heating of carbon nanotube composite materials, ACS Appl. Mater. Interfaces 10 (2018), 27252–910.1021/acsami.8b06268.
[50] GJ Sweeney, PF Monaghan, MT Brogan, SF. Cassidy, Reduction of infra-red heating cycle time in processing of thermoplastic composites using computer modelling, Compos. Manuf. 6 (1995) 255–262, https://doi.org/10.1016/0956-7143(95)95018-T.
[51] O Lucia, P Maussion, EJ Dede, JM. Burdio, Induction heating technology and its applications: Past developments, current technology, and future challenges, IEEE Trans. Ind. Electron. 61 (2014), https://doi.org/10.1109/TIE.2013.2281162, 2509–20.
[52] WT. Hill, Electromagnetic Radiation. digital Encyclopedia of Applied Physics, Wiley-VCH Verlag GmbH & Co. KGaA, Weinheim, Germany, 2009, pp. 1–26, https://doi.org/10.1002/3527600434.eap112.pub3.
[53] Woo Il Lee, Springer GS, Microwave curing of composites, J. Compos. Mater. 18 (1984) 387–409, https://doi.org/10.1177/002199838401800405.
[54] FYC Boey, CY. Yue, Interfacial strength of a microwave-cured epoxy-glass composite, J. Mater. Sci. Lett. 10 (1991), https://doi.org/10.1007/BF00722652, 1333–4.
[55] F Boey, I Gosling, SW. Lye, High-pressure microwave curing process for an epoxy-matrix/glass-fibre composite, J. Mater. Processing Technol. 29 (1992), https://doi.org/10.1016/0924-0136(92)90445-X, 311–9.
[56] M Kwak, P Robinson, A Bismarck, R. Wise, Microwave curing of carbon–epoxy composites: Penetration depth and material characterisation, Compos. Part A: Appl. Sci. Manuf. 75 (2015) 18–27, https://doi.org/10.1016/j.compositesa.2015.04.007.
[57] Kwak M, Robinson P, Bismarck A, Wise R. Curing of composite materials using the recently developed hephaistos microwave. 18th Int. Conference on Compos. Mater., 2011, p. 21–6.
[58] M. Kwak, Microwave Curing of Carbon-Epoxy Composites: Process Development and Material Evaluation, Imperial College London, 2016.
[59] C Nightingale, RJ. Day, Flexural and interlaminar shear strength properties of carbon fibre/epoxy composites cured thermally and with microwave radiation, Compos. - Part A: Appl. Sci. Manuf. 33 (2002), https://doi.org/10.1016/S1359-835X(02)00031-3, 1021–30.
[60] X Xu, X Wang, R Wei, S. Du, Effect of microwave curing process on the flexural strength and interlaminar shear strength of carbon fiber/bismaleimide composites, Compos. Sci. Technol. 123 (2016), https://doi.org/10.1016/J.COMPSCITECH.2015.11.030, 10–6.
[61] X Xu, X Wang, Q Cai, X Wang, R Wei, S. Du, Improvement of the compressive strength of carbon fiber/epoxy composites via microwave curing, J. Mater. Sci. Technol. 32 (2016), https://doi.org/10.1016/J.JMST.2015.10.006, 226–32.
[62] DA Papargyris, RJ Day, A Nesbitt, D. Bakavos, Comparison of the mechanical and physical properties of a carbon fibre epoxy composite manufactured by resin transfer moulding using conventional and microwave heating, Compos. Sci. Technol. 68 (2008), https://doi.org/10.1016/J.COMPSCITECH.2008.01.010, 1854–61.
[63] R Yusoff, M Aroua, N A, RJ Day, Curing of polymeric composites using microwave resin transfer moulding (RTM), Eng. Sci. Technol. 2 (2007) 151–163.
[64] N Li, Y Li, X Hao, J. Gao, A comparative experiment for the analysis of microwave and thermal process induced strains of carbon fiber/bismaleimide composite materials, Compos. Sci. Technol. 106 (2015) 15–19, https://doi.org/10.1016/j.compscitech.2014.10.008.
[65] ET Thostenson, TW. Chou, Microwave and conventional curing of thick-section thermoset composite laminates: Experiment and simulation, Polymer Compos. 22 (2001) 197–212, https://doi.org/10.1002/PC.10531.
[66] N Li, Y Li, J Jelonnek, G Link, J. Gao, A new process control method for microwave curing of carbon fibre reinforced composites in aerospace applications, Compos. Part B: Eng. 122 (2017) 61–70, https://doi.org/10.1016/j.compositesb.2017.04.009.
[67] B Nuhiji, MP Bower, T Swait, V Phadnis, RJ Day, RJ. Scaife, Simulation of carbon fibre composites in an industrial microwave, Mater. Today: Proceedings 34 (2021) 82–92, https://doi.org/10.1016/j.matpr.2020.01.284.
[68] LE Feher, MK. Thumm, Microwave innovation for industrial composite fabrication - The HEPHAISTOS technology, IEEE Trans. Plasma Sci. (2004), https://doi.org/10.1109/TPS.2004.823983.
[69] ET Thostenson, T-W. Chou, Microwave processing: fundamentals and applications, Compos. Part A: Appl. Sci. Manuf. 30 (1999) 1055–1071, https://doi.org/10.1016/S1359-835X(99)00020-2.
[70] X Hang, Y Li, X Hao, N Li, Y. Wen, Effects of temperature profiles of microwave curing processes on mechanical properties of carbon fibre–reinforced composites, Proceedings of the Institution of Mech. Eng., Part B: Jo. Eng. Manuf. 231 (2017), https://doi.org/10.1177/0954405415596142, 1332–40.
[71] E Díaz, R Emmerich, M Graf, C Ress, I Roig, L. Chamudis, Microwave Curing of Long Fiber Reinforced Composites in an Open Antenna System, 15, ECCM, Venice, 2012.
[72] N Pantelelis, E Bistekos, R Emmerich, P Gerard, A Zoller, RR. Gallardo, Compression RTM of reactive thermoplastic composites using microwaves and cure monitoring, Procedia CIRP 85 (2020) 246–251, https://doi.org/10.1016/j.procir.2019.10.005. Elsevier B.V.
[73] VK Rangari, MS Bhuyan, S. Jeelani, Microwave curing of CNFs/EPON-862 nanocomposites and their thermal and mechanical properties, Compos. Part A: Appl. Sci. Manuf. (2011), https://doi.org/10.1016/j.compositesa.2011.03.014.
[74] N Uyanık, AR Erdem, MF Can, MS. Çelik, Epoxy nanocomposites curing by microwaves, Polym. Eng. Sci. 46 (2006), 1104–10. 10.1002/pen.20574.
[75] C Joseph, C. Viney, Electrical resistance curing of carbon-fibre/epoxy composites, Compos. Sci. Technol. 60 (2000) 315–319, https://doi.org/10.1016/S0266-3538(99)00112-8.
[76] H. Fukuda, Processing of carbon fiber reinforced plastics by means of Joule heating, Adv. Compos. Mater. (1993), https://doi.org/10.1163/156855194X00015.
[77] Naskar AK, Edie DD. Consolidation of reactive ultem powder-coated carbon fiber tow for space structure composites by resistive heating n.d. 10.1177/0021998306061300, 2005.
[78] Athanasopoulos N, Sotiriadis G, Kostopoulos V. A study on the effect of Joule-heating during the liquid composite molding (LCM) process and on the curing of CFRP composite laminates. The 10th International Conference on Flow Processes in Composite Materials (FPCM10), 2010, p. p5.
[79] J Lee, X Ni, F Daso, X Xiao, D King, JS Gómez, et al., Advanced carbon fiber composite out-of-autoclave laminate manufacture via nanostructured out-of-oven conductive curing, Compos. Sci. Technol. (2018), https://doi.org/10.1016/j.compscitech.2018.02.031.
[80] A-T Chien, S Cho, Y Joshi, S. Kumar, Electrical conductivity and Joule heating of polyacrylonitrile/carbon nanotube composite fibers, Polymer (Guildf) (2014) 55, https://doi.org/10.1016/j.polymer.2014.10.064.
[81] SA Sarles, DJ. Leo, Consolidation of U-Nyte epoxy-coated carbon-fiber composites via temperature-controlled resistive heating, J. Compos. Mater. 42 (2008) 2551–2566, https://doi.org/10.1177/0021998308097197.
[82] J Reese, M Vorhof, G Hoffmann, K Böhme, C. Cherif, Joule heating of dry textiles made of recycled carbon fibers and PA6 for the series production of thermoplastic composites, J. Eng. Fibers and Fabrics 15 (2020), 155892502090582, https://doi.org/10.1177/1558925020905828.
[83] J Wellekötter, C. Bonten, Influence of the contacting on the resistance heating of carbon fiber reinforced thermoplastics, AIP Conference Proceedings (2020), https://doi.org/10.1063/5.0029567, 2289:20063.
[84] S Liu, Y Li, S Xiao, T. Wu, Self-resistive electrical heating for rapid repairing of carbon fiber reinforced composite parts, J. Reinforced Plastics and Compos. 38 (2019) 495–505, https://doi.org/10.1177/0731684419832793.
[85] JS Weiland, MP Hartmann, RM. Hinterhölzl, Cure simulation with resistively in situ heated CFRP molds: Implementation and validation, Compos. Part A: Appl. Sci. Manuf. 80 (2016) 171–181, https://doi.org/10.1016/j.compositesa.2015.10.020.
[86] FS Xoan, A Sans, A Jim, M Campo, A Ureña, SG. Prolongo, Highly multifunctional GNP /epoxy nanocomposites : from strain-sensing to joule heating applications, Nanomaterials 10 (2020), https://doi.org/10.3390/nano10122431.
[87] T Xia, D Zeng, Z Li, RJ Young, C Vallés, IA. Kinloch, Electrically conductive GNP/epoxy composites for out-of-autoclave thermoset curing through Joule heating, Compos. Sci. Technol. 164 (2018) 304–312, https://doi.org/10.1016/j.compscitech.2018.05.053.
[88] X Xu, Y Zhang, J Jiang, H Wang, X Zhao, Q Li, et al., In-situ curing of glass fiber reinforced polymer composites via resistive heating of carbon nanotube films, Compos. Sci. Technol. 149 (2017), https://doi.org/10.1016/j.compscitech.2017.06.001, 20–7.
[89] B Mas, JP Fernández-Blázquez, J Duval, H Bunyan, JJ. Vilatela, Thermoset curing through Joule heating of nanocarbons for composite manufacture, repair and soldering, Carbon N Y 63 (2013), https://doi.org/10.1016/j.carbon.2013.07.029, 523–9.

[90] C Li, RA. Dickie, Bonding adhesive joints with radio-frequency dielectric heating, Int. J. Adhes. Adhesives 11 (1991), https://doi.org/10.1016/0143-7496(91)90007-5, 241–6.
[91] A Vashisth, RE Healey, MJ Pospisil, JH Oh, MJ. Green, Continuous processing of pre-pregs using radio frequency heating, Compos. Sci. Technol. 195 (2020), 108211, https://doi.org/10.1016/j.compscitech.2020.108211.
[92] S Yarlagadda, HJ Kim, JW Gillespie, NB Shevchenko, BK. Fink, A study on the induction heating of conductive fiber reinforced composites, J. Compos. Mater. 36 (2002), https://doi.org/10.1106/002199802023171, 401–21.
[93] C Severijns, ST de Freitas, JA. Poulis, Susceptor-assisted induction curing behaviour of a two component epoxy paste adhesive for aerospace applications, Int. J. Adhes. Adhesives 75 (2017) 155–164, https://doi.org/10.1016/j.ijadhadh.2017.03.005.
[94] R Rudolf, P Mitschang, M. Neitzel, Induction heating of continuous carbon-fibre-reinforced thermoplastics, Compos. Part A: Appl. Sci. Manuf. 31 (2000) 1191–1202, https://doi.org/10.1016/S1359-835X(00)00094-4.
[95] TJ Ahmed, D Stavrov, HEN Bersee, A. Beukers, Induction welding of thermoplastic composites-an overview, Compos. Part A: Appl. Sci. Manuf. 37 (2006), https://doi.org/10.1016/j.compositesa.2005.10.009, 1638–51.
[96] T Bayerl, M Duhovic, P Mitschang, D. Bhattacharyya, The heating of polymer composites by electromagnetic induction - a review, Compos. Part A: Appl. Sci. Manuf. 57 (2014) 27–40, https://doi.org/10.1016/j.compositesa.2013.10.024.
[97] S Mahdi, H-J Kim, BA Gama, S Yarlagadda, JW. Gillespie, A comparison of oven-cured and induction-cured adhesively bonded composite joints, J. Compos. Mater. 37 (2003) 519–542, https://doi.org/10.1177/0021998303037006776.
[98] TE Tay, BK Fink, SH McKnight, S Yarlagadda, JW. Gillespie, Accelerated curing of adhesives in bonded joints by induction heating, J. Compos. Mater. 33 (1999), https://doi.org/10.1177/002199839903301704, 1643–64.
[99] Johnson RJ, Pitchumani R. Active control of reactive resin flow in a vacuum assisted resin transfer molding (VARTM) process n.d. 10.1177/0021998308091264, 2008.
[100] M Frauenhofer, H Kunz, Dilger, Fast curing of adhesives in the field of CFRP, The J. Adhes. 88 (2012) 406–417, https://doi.org/10.1080/00218464.2012.660386.
[101] A Sánchez Cebrián, R Basler, F Klunker, M. Zogg, Acceleration of the curing process of a paste adhesive for aerospace applications considering cure dependent void formations, Int. J. Adhes. Adhesives 48 (2014), https://doi.org/10.1016/j.ijadhadh.2013.09.029, 51–8.
[102] M Kim, H Kim, W. Lee, Repair of aircraft structures using composite patches bonded through induction heating, Adv. Compos. Mater. 24 (2015) 307–323, https://doi.org/10.1080/09243046.2014.899553.
[103] M Ramulu, PB Stickler, NS McDevitt, IP Datar, D Kim, MG. Jenkins, Influence of processing methods on the tensile and flexure properties of high temperature composites, Compos. Sci. Technol. 64 (2004), https://doi.org/10.1016/j.compscitech.2003.12.008, 1763–72.
[104] FYC Boey, TH. Lee, Electromagnetic radiation curing of an epoxy/fibre glass reinforced composite, Int. J. Radiation Appl. Instrumentation Part C Radiation Phys. Chem. 38 (1991) 419–423, https://doi.org/10.1016/1359-0197(91)90118-L.
[105] S Chandrasekaran, S Ramanathan, T. Basak, Microwave material processing-a review, AIChE J. 58 (2012) 330–363, https://doi.org/10.1002/AIC.12766.
[106] TP Naik, I Singh, AK. Sharma, Processing of polymer matrix composites using microwave energy: A review, Compos. Part A: Appl. Sci. Manuf. 156 (2022), 106870, https://doi.org/10.1016/J.COMPOSITESA.2022.106870.
[107] J Zhou, Y Li, Z Zhu, E Xu, S Li, S. Sui, Microwave heating and curing of metal-like CFRP laminates through ultrathin and flexible resonance structures, Compos. Sci. Technol. (2022) 218, https://doi.org/10.1016/J.COMPSCITECH.2021.109200.
[108] J Zhou, Y Li, S Liu, Y Zhang, P Wang, S. Sui, Zone-regulated microwave heating of CFRP laminates via ultrathin and flexible resonance structures with different working frequencies, Compos. Commun. 29 (2022), 101016, https://doi.org/10.1016/J.COCO.2021.101016.
[109] RR Mishra, AK. Sharma, Microwave-material interaction phenomena: Heating mechanisms, challenges and opportunities in material processing, Compos. Part A: Appl. Sci. Manuf. 81 (2016) 78–97, https://doi.org/10.1016/j.compositesa.2015.10.035.
[110] AJ. Bur, Dielectric properties of polymers at microwave frequencies: a review, Polymer (Guildf) 26 (1985) 963–977, https://doi.org/10.1016/0032-3861(85)90216-2.
[111] D Kim, T Centea, SR. Nutt, Out-time effects on cure kinetics and viscosity for an out-of-autoclave (OOA) prepreg: Modelling and monitoring, Compos. Sci. Technol. 100 (2014) 63–69, https://doi.org/10.1016/j.compscitech.2014.05.027.
[112] AMRC. Monitoring thermal distribution optris IR camera. n.d, 2015.
[113] E Rudolf, Final report summary - CODE (Curing polyester resins on demand, CORDIS - EU Commision (2007).
[114] Inma Roig Asensi, Rudolf Dr, Emmerich, Liliana Chamudis Varan. EP2062930A1 - Method and resin system for producing plastics mouldings having a cured plastics matrix -, Google Patents (2009).
[115] AIMPLAS, WAVECOM summary report. (2014).
[116] Borrás AB, Galindo B, Ramos F. Microwave heating of polymers: Influence of carbon nanotubes and graphene dispersion on the microwave susceptor effectiveness. 6th International Conference on Carbon Nanoparticle Based Composites, Dresden, Germany: 2013.
[117] Tuncer E, Sauers I, James R. Electrical properties of epoxy resin based nano-composites 2007. 10.1088/0957-4484/18/2/025703.
[118] JC Abry, S Bochard, A Chateauminois, M Salvia, G Giraud, In situ detection of damage in CFRP laminates by electrical resistance measurements, Compos. Sci. Technol. 59 (1999) 925–935, https://doi.org/10.1016/S0266-3538(98)00132-8.
[119] JB Park, T Okabe, N. Takeda, New concept for modeling the electromechanical behavior of unidirectional carbon-fiber-reinforced plastic under tensile loading, Smart Mater. Structures 12 (2003) 105–114, https://doi.org/10.1088/0964-1726/12/1/312.
[120] D Stavrov, HEN. Bersee, Resistance welding of thermoplastic composites-an overview, Compos. Part A: Appl. Sci. Manuf. 36 (2005) 39–54, https://doi.org/10.1016/j.compositesa.2004.06.030.
[121] D Brassard, M Dubé, JR. Tavares, Resistance welding of thermoplastic composites with a nanocomposite heating element, Compos. Part B: Eng. 165 (2019) 779–784, https://doi.org/10.1016/j.compositesb.2019.02.038.
[122] C Robert, T Pecur, JM Maguire, AD Lafferty, ED McCarthy, Brádaigh CMÓ, A novel powder-epoxy towpregging line for wind and tidal turbine blades, Compos. Part B: Eng. 203 (2020) 1359–8368, https://doi.org/10.1016/j.compositesb.2020.108443.
[123] J Lee, X Ni, F Daso, X Xiao, D King, J Sánchez Gómez, et al., Supplementary materials: advanced carbon fiber composite out-of-autoclave laminate manufacture via nanostructured out-of-oven conductive curing, Compos. Sci. Technol. 166 (2018), https://doi.org/10.1016/j.compscitech.2018.02.031, 150–9.
[124] Thermo Energy Corporation. EPRl Radio-Frequency Dielectric Heating in Industry. California: 1987.
[125] A Riccio, A Russo, A Raimondo, P Cirillo, A. Caraviello, A numerical/experimental study on the induction heating of adhesives for composite materials bonding, Mater. Today Commun. 15 (2018) 203–213, https://doi.org/10.1016/j.mtcomm.2018.03.008.
[126] Rudnev V, Loveless D, Cook R. Handbook of induction heating valery. 2017. 10.1201/9781315117485-3.
[127] T Segreto, A Bottillo, B Palmieri, L Nele, R. Teti, Ultrasonic evaluation of induction heat treatment applied to thermoplastic matrix CFRP, Procedia CIRP 88 (2020) 467–472, https://doi.org/10.1016/j.procir.2020.05.081. Elsevier B.V.
[128] DA McCarville, HA. Schaefer, Processing and Joining of Thermoplastic Composites, Compos. ASM Int.; (2001) 633–645, https://doi.org/10.31399/asm.hb.v21.a0003425.
[129] JB Khan, AC Smith, PM Tuohy, M Gresil, C. Soutis, Three-dimensional finite-element analysis multiphysics modelling of electromagnetic Joule heating in carbon fibre composites, IET Electr. Power Appl. 14 (2020), https://doi.org/10.1049/iet-epa.2019.0963, 1966–73.
[130] Kim D, Ramulu M, Doan AX. Influence of consolidation process on the drilling performance and machinability of PIXA-M and PEEK thermoplastic composites. J. Thermoplastic Compos. Mater. 2005;18. 10.1177/0892705705044556.
[131] KJ Åström, T. Hägglund, PID controllers: theory, design, and tuning 2 (1995).
[132] Vaidya S, Ambad P, Bhosle S. Industry 4.0 - A glimpse. Procedia Manuf., vol. 20, Elsevier B.V.; 2018, p. 233–8. 10.1016/j.promfg.2018.02.034.
[133] V Alcácer, V. Cruz-Machado, Scanning the industry 4.0: a literature review on technologies for manufacturing systems. engineering science and technology, An Int. J. 22 (2019) 899–919, https://doi.org/10.1016/j.jestch.2019.01.006.
[134] JL. Koenig, Spectroscopy of Polymers, Second Edition, American Chemical Society, 1999.
[135] S Liu, VS Chevali, Z Xu, D Hui, H. Wang, A review of extending performance of epoxy resins using carbon nanomaterials, Compos. Part B: Eng. 136 (2018) 197–214, https://doi.org/10.1016/j.compositesb.2017.08.020.
[136] V Kostopoulos, A Masouras, A Baltopoulos, A Vavouliotis, G Sotiriadis, L. Pambaguian, A critical review of nanotechnologies for composite aerospace structures, CEAS Space J. 9 (2017) 35–57, https://doi.org/10.1007/s12567-016-0123-7.
[137] H Tertrais, A Barasinski, F. Chinesta, Simulation of the propagation of an electromagnetic field in a laminated composite part: Application to microwave heating, AIP Conference Proceedings 1769 (2016), 170037, https://doi.org/10.1063/1.4963593.
[138] H Tertrais, R Ibanez, A Barasinski, C Ghnatios, F. Chinesta, Simulation of microwave heating of a composite part in an oven cavity, AIP Conference Proceedings (2017), https://doi.org/10.1063/1.5008005, 1896:30018.
[139] M Kim, DH Sung, K Kong, N Kim, BJ Kim, HW Park, et al., Characterization of resistive heating and thermoelectric behavior of discontinuous carbon fiber-epoxy composites, Compos. Part B: Eng. 90 (2016) 37–44, https://doi.org/10.1016/j.compositesb.2015.11.037.
[140] P Mitschang, R Rudolf, M. Neitzel, Continuous induction welding process, modelling and realisation, J. Thermoplastic Compos. Mater. 15 (2002) 127–153, https://doi.org/10.1106/089270502021451.