



Land, Patrick and Crossley, Richard and Branson, David T. and Ratchev, Svetan (2016) Technology review of thermal forming techniques for use in composite component manufacture. SAE International Journal of Aerospace, 9 (1). pp. 81-89. ISSN 1946-3901

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Technology Review of Thermal Forming Techniques for use in Composite Component Manufacture

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ABSTRACT

There is a growing demand for composites to be utilised in the production of large-scale components within the aerospace industry. In particular the demand to increase production rates indicates that traditional manual methods are no longer sufficient, and automated solutions must be sought. This typically leads to automated forming processes where there are a limited number of effective options. The need for forming typically arises from the inability of layup methods to produce complex geometries of structural components. This paper reviews the current state of the art in automated forming processes, their limitations and variables that affect performance in the production of large scale components. In particular the paper will focus on the application of force and heat within secondary forming processes. It will then review the effects of these variables against the structure of the required composite component and identify viability of the technology. Through this, an understanding of the key criteria involved in the forming of composite aerospace components can be utilised to better inform improved manufacturing processes and capabilities.

CITATION: Land, P., Crossley, R., Branson, D., and Ratchev, S., "Technology Review of Thermal Forming Techniques for use in Composite Component Manufacture," *SAE Int. J. Mater. Manf.* 9(1):2016, doi:10.4271/2015-01-2610.

INTRODUCTION

There is increasing demand for the use of lighter and stronger materials for use within the aerospace industry in structural applications. Composites in particular are emerging as a potential solution to the demands of modern commercial aerospace companies as shown by the use of over 50% of the A350 structure being comprised of composite [1, 2].

With the development of composite materials and forming methods it is possible to achieve a wide variety of shapes and forms through methods such as vacuum and diaphragm forming. However, these processes are often expensive for large parts and are limited to specific geometry with medium to low production rates depending on the component. There is increasing interest in how to enhance these current methods for use in composites manufacture [3]. In future, the combination of existing technologies into hybrid technologies may offer solutions to transform the capabilities of current composite forming.

This paper will review the following technologies looking at a variety of stages of composite forming, layup, and curing:-

- Layup Technologies:
 - Pick and Place
 - Automated Tape Layup (ATL)
 - Automated Fibre Placement (AFP)
 - Out of Autoclave Methods
- Forming Technologies:

- Diaphragm Forming/ Double diaphragm forming
- Drape Forming
- Curing Processes:
 - Vacuum Bagging
 - Autoclave Curing
 - Thermoplastic in-situ consolidation
 - Co-curing
- Net-shape manufacture and curing:
 - Resin Infusion (Resin Transfer Moulding)-RTM
 - Same Qualifies Resin Transfer Moulding -SQRTM

These technologies include automated and manual technologies that are currently used in industrial applications. Consideration of the advantages and disadvantage of these methods will be made, and their potential use in the forming of complex geometries will be assessed.

This paper will then focus on the factors surrounding the thermoforming of composites and how these factors can vary. It will include a study of the various defects that can form in composite manufacture, and how the process of forming composites can affect the formation of defects. The paper is organised into the following sections:-

- **Background** - Brief overview of thermoforming and outlining the technology and its development.
- **Processing Requirements** - Discussing the common requirements when thermoforming composite structures for use in aerospace applications.

- **Materials Requirements** - Discussion of the requirements on materials to be formed using thermoforming techniques.
- **Composite forming defects** - listing common composite forming defects and their causes.
- **Composites manufacture technology** - Detailing current industrial practice in the production of components for use in the transport industry.
- **Thermoforming manufacture technology** - Specific outline of thermoforming technology and its use in manufacturing.
- **Examples of thermoformed Aerospace Components**
- **Next generation use of thermoforming** - Discussion of the potential next generation application of thermoforming processes to composites manufacture.
- **Summary and conclusions**

BACKGROUND

Thermal forming technology is not a new manufacturing principle with patents for polymer sheet thermal forming technologies dating back to the first half of the 20th century[4]. Early thermal forming technologies used vacuum to apply the required forming pressure, with early heating methods including hot oil baths and infra-red lamps. Even with the use of basic technologies the variables associated with heating and pressure application within the process are of high importance depending on the type and thickness of polymers used. During the 1940's thermoforming of polymers expanded to the use of various heating systems including convection heating, there was also shift with the application of pressure from only vacuum technology to the use of vacuum and pressure in the form of moulds. These innovations lead onto a period of technological prominence, a 'golden-age', for thermoforming of polymer materials[5].

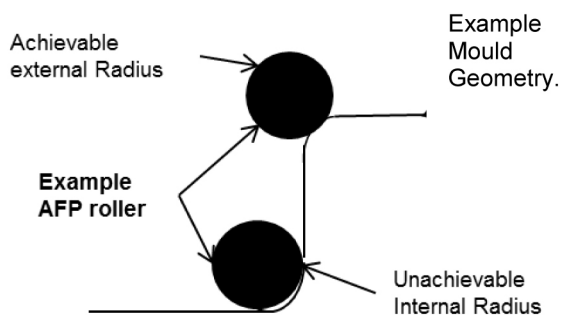


Figure 1. Example of geometrical limitations with existing AFP/ATL equipment.

More recently, alternative automated processes have also been developed for production of relatively simple components, including pick and place, AFP, and ATL. However, these technologies are limited in that they cannot always follow the contours of complex moulds and mandrels and are unable to deliver the required consolidation pressure during placement (figure 1). This tends to be a mechanical issue as the head or roller size on current layup

technologies restricts what internal contours can be reached. Geometrically complex external features also result in significantly reduced layup rates due to the complexities of tape or tow steering. The time required to layup large structures manually or for automated application is often hours and days rather than the minutes and seconds needed by industry with significant negative impact on production rates and costs [6]. Therefore, a manufacturer may seek enable layup or increase rates by flat part layup with a subsequent forming operation.

PROCESSING REQUIREMENTS

When considering thermoforming processes a common theme is the use of heating systems which must focus on delivering heat uniformly. Then the application of force either via vacuum, matched die moulds or the use of direct pressure such as in an autoclave.

When considering thermoplastic materials a critical feature is the ability to raise the temperature of the material to higher than the glass temperature, T_g , for amorphous polymers and T_m , for semi-crystalline polymers, typically over 120°C is required depending on the polymer to be formed.

Thermoset polymers typically used in aerospace, are mostly above their uncured T_g at room temperature. However, a rise in temperature of 20-60°C is typically required for forming, primarily to reduce the viscosity of the material[7]. However, this can be detrimental to the shelf life of the material due to the advancement of the cure reaction, which is also likely to cause an increase in viscosity over time depending on the resin cure kinetics.

As most forming processes require the application of force, it is important to understand how this is applied and the best application method for the required geometries. This is largely to reduce the risk of part thinning and any changes in the mechanical properties of the material that could be detrimental to component performance. To reduce this it is common to use methods that offer the potential for uniform force distribution, such as vacuum or pressure membranes, to ensure even loading and reduce the risk of localised thinning or wrinkling [8].

An additional concern in the thermoforming process is the accurate clamping of the material. This is a vital factor as the deformation of the polymer or composite should be uniform in all directions. To achieve uniform deformation the materials should be clamped equally on all sides, ensuring that the materials remain in uniform tension during the process and do not allow non-uniform features or defects [9]. There are a variety of clamping mechanisms used in thermoforming technologies. Two common examples are the Clamp frame (Figure 2), which essentially clamps the material in a frame similar to a glass pane in a window frame [10]. The other is transport-chain mechanisms, often used for large scale applications where a large sheet is held between two hooked chains and pulled through [9].



Figure 2. Example of a thermoforming clamp frame for the use in vacuum forming [11].

The Above process requirements form the critical backbone of the technology and should all be taken into account when considering adapting the technology for composite components in other industries such as aerospace.

MATERIALS REQUIREMENTS

Within the composite industry there are two types of polymer resin systems; thermoset materials and thermoplastic materials. A Key difference in these two polymers is the molecular structure. Thermosets when cured have a strong irreversible cross linked structure that provides a solid matrix and is highly solvent resistant. As such, this matrix material can only be formed before it has cured. Since the cure reaction is accelerated by heat, the key challenge is application of heat and forming must be carried out within a relatively short period of time. The application of heat is required to lower the resin viscosity enough to flow before it begins to cure [12].

Thermoplastics have either amorphous or semi-crystalline structures, indicating no permanent network structure between chains is formed. This allows molecules to move with the introduction of heat they can be formed multiple times and the material is effectively solid at room temperature. To allow thermoplastic resins to be formed the composite must be heated to much higher temperatures than thermosets then large forces applied to consolidate the resin, this is largely due to the high viscosity of the matrix material. Thermoplastics also have the issue of being susceptible to solvents and other degrading materials [12]. Although these materials show greater compatibility with the forming process and show promise as a material of the future [13], they are rarely used in current production of large structural aerospace components.

A general rule with curing is to ensure heating of the material to the specified curing schedule. However, this has inherent issues in thermoset resins as the temperature raises the viscosity lowers making it more formable. This feature is key to the forming of thermoset composites however it restricts the time scale in which you can form the material. Additionally, limiting the time a material is at higher than ambient temperatures can reduce the risk of issues such as partial curing. Following these precautions we can reduce the chance of curing based defects in the production of composite components [14]. Other factors that can affect the materials properties

of composite components are forming defects such as wrinkles or fibre defects. These are difficult to detect and are often only found after forming and curing of a part [15].

There is a wide range of material requirements that can arise based on application, material properties, etc. It is therefore important to ensure that the correct material characteristics are achieved for the component. Additionally, it is also important to consider the materials requirements for forming. Within this second point it is important to determine how the forming process can affect the material life and properties. As composite materials often require curing, a process that can be achieved by pressure and temperature or both of these features. It is vital to understand ways of reducing the chance of curing causing adverse effects on the material during forming operations [16, 17].

As the above shows there are a variety of requirements, both on the process and materials that can significantly affect the outcome of a forming process and quality of components. Using technologies such as thermoforming provides great potential. However, specific materials often require unique forming conditions. This is a critical factor in the development of this technology for use on advanced composites [18]. As composite materials develop to the requirements of a rapidly growing Industry, materials suppliers don't provide data sheets to aid in the design of forming operations on composite materials. Often extensive experimental research is required to acquire the forming parameters and this process is specific to the material and layup.

COMPOSITE FORMING DEFECTS

With all of the above technologies there are a number of factors leading to the formation of defects in the composite materials. This can result in the need for components to be scrapped or to reduced mechanical performance resulting in re-work. Considering specifically thermoforming of composite materials the common sources of failure are due to:

- Formation of wrinkles within the ply
- Waviness or buckling in the fibres
- Dragging of plies or fibres
- Partial curing resulting in voids during cure
- Localised thinning

These defects are an area of extensive research in composites manufacturing as they can determine the pass/fail criteria for a wide variety of composite components[19].

Defects in composites can be caused by incorrect specification of processing parameters such as temperature and pressure. Studies on the effects of processing parameters on forming show that there are heightened risks of wrinkles when forming at lower temperatures. Studies have also shown that using slower forming speeds produced fewer defects as there is a decrease in interply friction during forming[14]. These effects vary significantly from material to material even within the same composite type and can be related to the layup or consolidation of the material. Studies have also shown

that changes in processing parameters can affect the interply friction and therefore result in the generation of defects. This can be due to changes in the resin viscosity or other interply properties such as the consolidation of the materials [20]. Changes in process variables can also affect prepreg tape, properties such as Tack and stiffness of the materials can be effected, with any variation in parameters these can be a cause of defects [21].

COMPOSITES MANUFACTURE TECHNOLOGY

Current industry practices with respect to composites manufacture can be broken into 3 main processes: (1) layup of materials using dry fibre or prepreg systems; (2) forming of these components and (3) curing of components. These stages form the general manufacturing process of composite components with some technologies being applicable to multiple processes.

Layup Technologies

These technologies form the first phase of composite manufacture. During this stage plies are collated to form the prepreg laminate or dry fibre pre-form depending on the process. In all methods this is typically the first stage of aerospace component manufacture with the prior components, such as prepreg, fibres and resin being outsourced. The plies can be collated using a number of methods detailed in the next section.

Pick and Place

The most common form of fibre layup is hand layup, this process is still widely used in the generation of high-quality composite parts. However, this process is cost intensive and difficult to achieve with large components, as such automated pick and place systems have been developed. This process can be completed with prepreg, using the tack of the material to hold it on place. Alternatively the process can be completed with dry fibres requiring additional stitching or a binder to hold the material in place.

This technology is based on building layups piece by piece. This is essentially a complex customised jigsaw made of reinforcing materials. This technology allows for large structures to be produced as dry preforms that have been bound together using small amounts of resin materials or using preformed prepreg sections formed to the required geometric pieces, and then the infusion and curing methods discussed later in this report used to produce the finished components [22]. This technology has the advantage of allowing for complex shapes to be produced without worrying about the curing of resins when using prepreg, and with dry preforms only one infusion phase is needed after the layup is set in place. A disadvantage is that this technology is slow and requires an infusion stage such as resin infusion or Vacuum Assisted Resin Transfer Moulding-VARTM to infuse the dry preform with matrix material.

Automated Tape Layup - ATL

ATL uses an automated system to place typically 25-250mm wide strips of fibre tape that already have been pre-impregnated with resin (prepreg) in the required direction to create large structures with

customised layups and fiber directions [23]. An advantage to this technology is that it can be used on a robotic system allowing for multiple axis motion, including large structures through the use of gantries etc. [23]. ATL is particularly suited to large flat or gently curved components. It is often unsuitable when producing more complicated geometries. This leads to a large amount of waste and the requirement of larger run-off areas and scrap courses than existing AFP methods. This technology is currently used in conjunction with double diaphragm forming on the production of wing spars for the airbus A400M by GKN in the UK [24]. The advantage of ATL over AFP is that higher rates of deposition are achievable. Equipment and materials can also be lower cost due to reduced complexity of the equipment and reduced slitting and spooling of the prepreg material.

Automated Fibre Placement - AFP

This method is used to create large structures for aerospace where more complex geometries or layups are required. The basic technology uses a roller to lay pre-impregnated fibre strips, often called "Tows" on to a single sided mould using heat and pressure. Through the use of automation, repeatability of part quality is easier to achieve [25]. This technology is currently used by GKN on the A350 XWB [26]. In this application prepreg tape similar to that used on the existing A400M wing spars, but in the form of smaller slit tows. These thin strips, typically between ¼" and ½" wide, of prepreg material are designed to enable the tool to steer around corners and radius while still laying materials up with less waste than ATL technologies [25].

In comparison to ATL, this technology is more capable of producing more complex geometries as the narrow composite tows are easier to guide. However, this incurs additional machine costs and reduced layup rates, particularly on complex geometry. Both ATL and AFP have geometrical limitations in that there is a limit to the amount of steering of the fibre around corners and steep internal contours are not accessible to the large machine head and roller diameter. Additionally, layup of complex geometry also significantly reduces the achievable lay-up rates.

Forming Technology

Forming requires the use of pressure and or temperature to ensure that the component is forced into the mould geometry. Often the forming of composites and the layup of the material as detailed above can be similar or even combined into a single process. However, a critical difference in these processing areas is the application method to achieve desired forces.

Diaphragm Forming/ Double Diaphragm Forming

Using temperature and vacuum pressure composite materials can be moulded through the use of a single or series of diaphragms with composite materials under or between them. This is accomplished in a heated vacuum atmosphere where pressure can be applied to the top surface also to aid in consolidation of the part. The vacuum must be applied evenly across the layer of materials and mould surface to form an accurate component [27]. In the case of single diaphragm forming the diaphragm is applied to the upper surface of the material, and force is applied to this, pressing the laminate into the mould

surface. However, as with most thermal forming technologies there is the issue of materials wrinkling due to the composite nipping or overlapping on itself in the mould. This failure method in composites is critical when looking at aerospace applications [28].

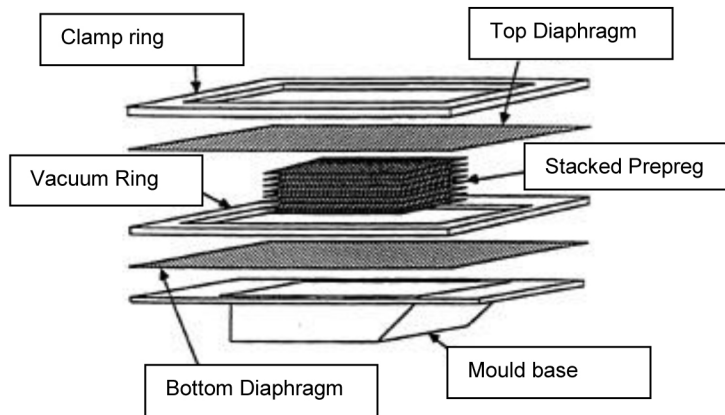


Figure 3. Schematic of double diaphragm system. [29]

Advantages of this technology are that it allows for forming and part curing in one operation. Additionally, this technology produces high quality components. Disadvantages of this technology are the time it requires to setup the process and limitations in the achievable geometries.

Drape forming

'Drape forming' can be used as a blanket term for any type of forming involving woven fabrics. Typically it involves the hand forming or pressing of plies over a complex geometry mould which is further consolidated by a vacuum bag or press. Using heating the resin matrix material is softened and made malleable, then draped over the desired mould surface. This is then bagged and placed in an autoclave for curing and consolidation. Using this technology small to medium sized composite component can be made in one single forming operation, which has the potential to shorten part production times dramatically [30]. But it is more likely that there will be part failures through wrinkling caused by interply shear issues [30].

There are additional time restrictions with drape forming as with other multiply forming technologies. To reduce the risk of voids forming in the material and other defects de-bulking operations can be required between plies throughout the process, which adds additional time and cost [31].

Curing Technology

This is the final phase in the production of composite components, the use of curing methods to consolidate and/or cure the composite depending on the material to form the final composite structure. This phase is vital in the formation of high quality composite parts with low levels of defects. The use of the correct forming methods can aid in the reduction of the risk of defects such as voids and wrinkles. However, the majority of forming operations should be complete before this stage of development or be designed with the curing phase in mind as composite forming is often a fluid process between the various stages [31, 32].

The composite must be heated to the required cure temperature with careful consideration such that this temperature is not overshoot due to control issues or the exothermic cure reaction. The consolidation pressure or hydrostatic resin pressure must remain high during the curing process to prevent the formation of voids [31].

Out of Autoclave Methods (Quickstep, Bladder Moulding)

In essence these technologies include any pressure curing activities not inside of a heated and pressurised environment such as an autoclave [33, 34, 35]. These groups of technologies are used to cure flat sheets and layups of composite materials into finished components. As with other curing technologies this group uses pressure usually in the form of air pressure in a variety of ways to give the required laminate pressure during cure.

The advantage of these types of technology is the reduced cost of curing components without the need for an expensive autoclave. The disadvantages of this technology is that it is often not able to achieve pressures and an even pressure distribution equivalent to an autoclave. Therefore, part quality and mechanical performance can suffer.

Vacuum Bagging

Vacuum bagging uses vacuum pressure to aid curing of composites and press the material into the mould by pulling a bag film over the composite and mould. Vacuum bagging utilises pressure to consolidate the composite laminate reducing the risks of voids and porosity occurring due to the formation of gas pockets during curing [31]. This pressure is from the bag materials being pulled on the materials making the specification of bagging material a critical feature in this curing process. This technology can be used for curing of prepreg materials while in an autoclave with vacuum pressure and autoclave pressure forming a low porosity component, or can be used in conjunction with resin transfer systems to Infuse and consolidate the mould and fabric material with the resin in the vacuum assisted resin transfer moulding process (VARTM) [36].

Vacuum bagging has the advantage of being applicable to a variety of components including large components. However, it is a lengthy process that requires significant time to set-up and work.

Autoclave Curing

When looking at the generation of high-quality composite components in aerospace the use of an autoclave for forming/curing is a widely used method [31]. This is essentially the application of heat and pressure to the formed component for a set period of time to consolidate and cure the composite component. Vacuum technologies are commonly used with this process to limit the nucleation of voids during the high temperature process. Control over the temperature and pressure applied in the autoclave over time is greatly important in reducing material shrinkage and build-up of residual stresses in the laminate [37].

Common advantages of the use of autoclave technologies include the generation of low void components typically less than 1%. Disadvantages to this technology include the cost of autoclaves and the control of heating in the autoclave to insure even heat distribution [31].

Thermoplastic in-situ Consolidation

This technology effectively allows the production of thermoplastic composite components that are cured in stages during the layup process. Parts are first heated and then consolidated under compaction resulting in the formation of parts traditionally without the use of an autoclave [38, 39]. This process uses significantly higher temperature heating to raise the temperature of the thermoplastic matrix material to well over T_g/T_m depending on amorphous/semi-crystalline materials respectively then applies pressure to allow the matrix materials to bond and impregnate the fibres forming a thermoplastic composite [31]. This technology gives us the advantage of enabling the manufacture of thermoplastic composites and consolidation of the laminate during layup using automated processes. Thermoplastics have great potential due to their formable nature and natural toughness. However, this materials choice is still not prominent in industry and is a developing technology largely due to the high viscosity of the matrix materials and the issues this presents in forming due to the need for high pressure press forming other methods such as vacuum bagging are not suitable [31].

Net-Shape Manufacture and Curing

Co-curing

When looking to create large fully composite structures there is a requirement to interface composites with each other, as done in the A350 XWB [40]. Amongst other technologies the use of both composite bonding and co-curing has the potential to produce fastener less assemblies in aerospace. Co-curing is the practice of curing two or more formed laminates in one operation joining them in the process. Co-bonding can also be used however this process produces a joint that is more difficult to detect than co-curing. These technologies provide a new direction for the use of composites in aerospace by offering the ability to produce part by part manufacture. With the ability to combined the final sub-assembly stage into the final manufacturing phase. This technology has the potential to enable more advanced structures however the technology is not easy to apply and often has costs higher than other curing processes.

Resin Infusion (Resin Transfer Moulding)-RTM

The use of resin infusion and Resin Transfer moulding is common in the generation of high quality composite components where further development of the process could offer a low-cost high quality forming application (VARTM) [41, 42]. In this process layup of dry fibres, such as in Pick and Place methods or hand layups are used. Then a cavity is made around the fibre form and resin injected into the cavity under pressure until it is full impregnation of the fibres ply is achieved this process often requires high pressure moulds with matched dies which carry a high initial capital investment in the case of RTM. The use of vacuum bagging technology with RTM (VARTM) has the potential to reduce costs however this technology currently doesn't provide components with low enough void % for structural aerospace applications this is specifically resin infusion as it only has one side of a die and uses lower pressure forming [31].

RTM has the benefit of using a full mould to ensure that the geometric tolerances are of a high standard. Also as the resin is injected into the fibre preform there is a reduction of any interply

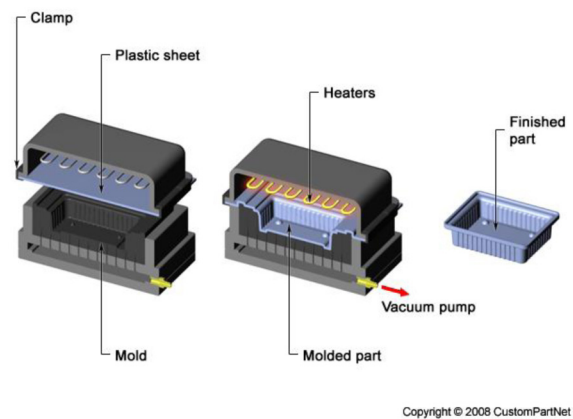
issues as the resin is injected through all of the plies in one operation. This technology has some issues on size as the resin needs to flow evenly in the cavity and it is also a time intensive process that does not generally fit application unless there production quantities justify the initial setup costs [31]. As mentioned above resin infusion with vacuum bagging is a lower cost alternative to RTM however it does produce lower quality components.

Same Qualified Resin Transfer Moulding - SQRTM

SQRTM (same qualified resin transfer moulding) is a very recent experimental process allowing for the infusion of resin into a prepreg structure within closed moulds. This allows for net shape manufacture of prepreg products with a greater repeatable dimensional accuracy and surface finish. Existing preregs and prepreg resin systems are used to eliminate the need to re-qualify the materials, reducing lead times and costs[43]. This method effectively uses closed moulds and infuses the same resin which is infused in the prepreg into the mould. This greatly reduces the void content in the composite without the use of an autoclave, improves part tolerances and allows for production of two quality surfaces [44]. This technology is a hybrid of prepreg layup systems and RTM mentioned above, where the advantage is in the generation of high quality parts using rapid layup technologies. A disadvantage to the technology is the additional time required to infuse the resin and the manufacture of complex matched die tooling that carried high initial costs as mentioned above.

POLYMER SHEET THERMOFORMING TECHNOLOGIES

Thermal forming technologies are a primary application in polymer forming [45]. The essential process is the application of heat to the material to raise it above its glass temperature, then the application of force most commonly applied through vacuum technology. This process is widely used in the forming of high capacity systems such as plastic cups where potentially millions of units can be produced per day [46]. As such this process is widely used in industry for a variety of products from food to medical devices.



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Figure 4. Overview of polymer thermoforming process. [47]

Thermoforming in polymer applications is similar to its use in other materials, the use of heat on the materials to raise the temperature to above T_g and then the application to force through vacuum of mechanic force to form components. There are various methods used in industry today samples of these methods are listed below.

- Vacuum forming
- Matched Die forming (Mechanical forming)
- Pressure forming

In all of the above examples the idea is the same heat is applied to a material that is clamped in place using various methods. Force is then applied either pulling the material into the mould cavity (Vacuum), Pushing it (Pressure) or pressing the material (Mechanical), as with composites the process is dependent on the material properties and the material thickness [47].

Although widely used in industry for polymer components, this technology is not currently used for more structural applications as often it required the use of relatively thin materials. Through developments in this technology with regards to new materials using natural fibres and full melt forming, there are increasing amounts of structural applications possible, such as automotive panels [48]. A critical issue with the use of fibre composites is the limiting of resin flow through the fibres that can inhibit the ability to form composites[49]. However, by using resins that are capable of use in thermoforming processes we can endeavour to use technologies applicable to those materials for composite structures. This will add much needed strength to the products and diversify the potential manufacturing methods applicable.

Throughout the above technologies and associated thermoforming examples the use of heat is critical to the success of this process. As such there is a variety of existing research into the use of various heating methods for thermoforming, with a focus on uniform heating through heater lamps (IR lamps), Oven based heating (Autoclave) and various of methods. The use of thermoforming has proven to be successful in polymers, with common forming problems such as spring-back being designed for, however the addition of fibres into the material causes significant issues such as wrinkling [32, 50].

EXAMPLES OF FORMING AEROSPACE COMPONENTS

There are a wide variety of components such as spars, ribs and skins for aerospace which are manufactured using composite materials in industry. Typically these components consist of unidirectional fibres for structural applications. Within the aerospace industry there are a wide variety of applications for composites including applications for both the wing and fuselage in a variety of aircraft [2, 51, 52]. The first example component is the use of composite forming technology to create a wing spar, GKN have developed the use of composite manufacturing technology in the form of AFP to produce large structural composite components [53]. This technology has also been used in the A400M components. However, with a focus on ATL technologies again for wing spars and structural applications [54].



Figure 5. A400M ATL machine process.[51]

Other components Include wing skins that can be of variable thicknesses and variable geometries placed at any point over the geometry of the wing. These can be made of a variety of composites from carbon composites to glass layered composites and other materials. These components and other composite wing parts have been shown to have significant benefits over conventional metallic wing options [55].



Figure 6. Complex Composite geometry from GKN. [56]

As the above component shows there is an increasing amount of components that can use composites in aerospace. This is due to their high strength-weight ratio and their ability to be formed into a variety of variable geometries. As new and more complex geometries can be mass produced on demand, the potential of composite components will only increase.

Forming Vs Net Shape Layup of Aerospace Components

Two relatively recent aerospace programs have made use of developments in composite manufacturing: the A400M and A350 Airbus aircraft that both use composite spar technologies. However, the manufacturing processes differ significantly due to the materials used. The A400M makes use of ATL technologies to layup large areas of flat composite sheet which is then formed into the Spar geometry. This technology is similar to the use of many thermoforming

technologies. The A350 Uses AFP technology to lay the spar directly onto a spar shaped mandrel such that it does not require a subsequent forming operation [57].

There are a variety of reasons for this including a simple difference in design that allows the A400M spar to be formed with more simplicity, to the change in composite material used [52]. As discussed earlier in this paper the processing parameters and their effects on composite materials can vary significantly from material to material, and for this reason the materials that were used in the A400M spar can be uniformly formed using the Faster ATL system. While the Hexcel materials used in the A350 system are reported to be more difficult to form. Further development and research of the forming process and material properties is required to give greater understanding that may enable a similar production process to the A400M. Looking at the geometry to be achieved and the materials being formed is a vital stage in effectively designing composite components for the best possible manufacturing operation. Such a design for manufacture approach can lead to significant time and cost savings if carried out to the appropriate level which is increasingly important in composite component manufacture [56].

NEXT GENERATION USE OF THERMOFORMING

Manufacturers are constantly seeking more complex and integrated components. This is driven by the increased benefits of reducing part number and the amount of part and assembly operations. This is currently limited by the limitations of forming technology and automation methods. Increasingly manufacturers look to combine processes and use existing technology but applied for composites as a potential method to achieve these complex integrated components.

When considering the forming of composite materials it is important to look at the existing alternative technologies. This is not only to evaluate competitor technologies, but also to inform overall technological process. The application of thermoforming techniques to composite applications will enable new forming technologies, increasing the use of composite materials and in turn increase the efficiency of many transport applications [58]. With the added benefit of reducing lead times for large CFRP components.

Therefore more reliable forming or more complex faster layup devices are required to satisfy this demand for complex integrated components. This has particular importance in the use of continuous fibre materials and thick ply applications where part quality and strength can often be a trade off against manufacturing times. Thick and integrated components are required to deliver the properties that are desirable for the use of CFRP materials in structural applications [59].

CONCLUSIONS

This technology review covers a variety of methods of forming for composites and provides lessons for the application of thermoforming to composite structures. The identification of the primary factors that affect thermoforming: heat, pressure and material; and manufacturing methods affecting these parameters were discussed. Control of these

primary factors can enable significant progression of the use of thermoforming in composite component manufacture. Looking at the development of thermoforming into industry there is a demand for large components such as spars, skins etc. to be produced using CFRP unidirectional tape (prepreg) with toughened epoxy resin systems. Attempts can be made to increase production rates with automation AFP/ATL, where layup of flat panels can be achieved much faster.

With this use of automation, forming of components into complex geometries with tight concave contours in particular that AFP/ATL is not capable has the requirement of secondary forming methods. The key issue here is however the difficult nature of forming CFRP, as such large series of trial and error methods are required, where defects such as part thinning and wrinkles are often an issue. The issue of forming especially with thermoforming is significantly more complex with CFRP than with simple polymers, this is due to the fibrous nature of continuous fibre composite materials.

As a result there appears to be very little understanding of the use of forming technologies on prepreg materials. This is ever present with the lack of any specification for forming or forming parameters being provided by materials manufacturers. This could be due to the apparent lack of an agreed standard series of test methods for forming parameters. With Heat and other forming parameters being critical for effective manufacturing of these materials there are no optimum values provided by manufacturers. Therefore, more research is required to define materials properties, processing parameters and the optimum machine configurations which give superior forming performance.

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DEFINITIONS/ABBREVIATIONS

AFP - Automated fibre placement

RTM + VARTM - Resin transfer moulding + Vacuum Assisted Resin Transfer Moulding

NDT - None destructive testing

ATL - Automated tape layup

CFRP - Carbon fibre reinforced polymer