

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.

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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].

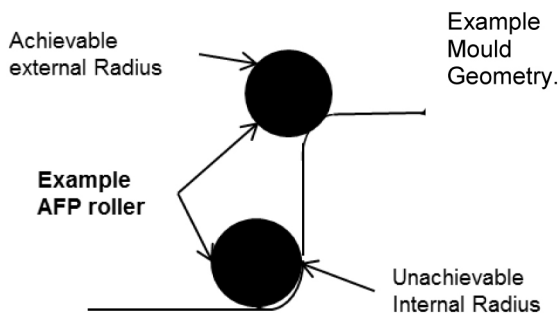


Figure 1. Example of geometrical limitations with existing AFP/ATL equipment.

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 layout.

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 layout or consolidation of the material. Studies have also shown