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A concept for the in situ consolidation of thermoset matrix prepreg during automated lay-up

Dirk H.-J.A. Lukaszewicz [*,1], Kevin D. Potter [2,4], Jonathan Eales [3]

Advanced Composites Centre for Innovation and Science (ACCIS), University of Bristol, Queen's Building, University Walk, Bristol BS8 1TR, UK

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ABSTRACT

Two major targets of current composites manufacturing research are the automation of lay-up and the development of vacuum bag only (VBO) cure. Currently regular debulk cycles are often required to obtain good as-laid quality, and autoclave cure is needed to obtain an adequate cured laminate quality. This paper will present data from a purpose-built automated lay-up simulator that has been developed to offer very well controlled lay-up. It is shown that high quality laminates may be manufactured without debulk cycles and cured under a vacuum bag without additional pressure by sufficiently compacting each ply during layup. This is achieved using layup temperatures and pressures falling outside the range attainable by the current generation of ATL/AFP machines and a development strategy is proposed to achieve the development of more capable equipment.

1. Introduction

Despite the relatively recent industrial take up of automated processes, the concepts behind the Automated Tape Laying (ATL) and Automated Fibre Placement (AFP) machines date back to patents issued in the early 1970s [1,2] and have seen limited development of the fundamental process principles. Recently, Lukaszewicz et al. [3] have published an extensive review of this area of composite manufacturing and have concluded that the scientific understanding of the process and material interactions during manufacture is limited. Layup pressure, temperature and speed are controlled in order to obtain reliable layup and it has been shown that AFP laminates achieve higher mechanical performance after autoclave cure than those manufactured manually [4]. However, it is often overlooked that layup machines are currently only employed to replace manual layup while the use of computer numeric control (CNC) may enable entirely different manufacturing approaches due to the possible repeatability and high degree of control. One such option is explored in this work, where layup at elevated pressure and temperatures is studied to compact each laid down ply to enable VBO-cure of autoclave only curable prepreg. Initially, the manufacturing processes are discussed and a generic set of manufacturing parameters is derived. A layup simulator is then introduced which emulates both AFP and ATL processing. The layup simulator was used to manufacture small coupons at layup temperatures and pressures currently not achievable with industrial equipment. The manufactured coupons were then studied for their voidage, thickness and inter-laminar shear strength (ILSS) after oven cure and this is discussed in the context of voidage in the final part.

1.1. Automated layup technology

ATL and AFP machines share many characteristics such as the use of numerically controlled deposition of preimpregnated reinforcements (prepreg) under carefully controlled conditions that include the delivery of the prepreg to the lay-up point on the tool under a controlled tension and, as needed, the removal and rewinding of backing paper under a controlled tension. Prepreg is applied at controlled temperature and with additional consolidation load to affix the prepreg to the tool or previously laid material. Both sorts of machines will also cut the prepreg plies at the end of each lay-down course and can operate at translational speeds of up to 1 m/s. The developmental drivers behind the two sorts of machines are essentially the same, to deliver cost efficient composite manufacture and to reduce the possibility of scrap and errors arising from manual lay-up.

The key difference between ATL and AFP machines lies in the width of the prepreg being handled. ATL machines utilise a single relatively wide tape of up to 300 mm wide, whereas AFP machines employ a multiplicity of narrow tapes, perhaps up to 32 tapes each

* Corresponding author. Tel.: +49 (0) 176 245 33023.
E-mail addresses: Dirk.Lukaszewicz@googlemail.com (D.H.-J.A. Lukaszewicz), K.Potter@bristol.ac.uk (K.D. Potter).
[1] Honorary Member of Staff.
[2] Professor in Composite Manufacture.
[3] Final Year Student.
[4] Tel.: +44 (0) 117 33 15277; fax: +44 (0) 117 927 2771.

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3–6 mm wide. In the AFP machines each tape is separately controlled for tension and can be cut and restarted individually. Although individually preimpregnated tows could be used in AFP it is more common to use narrow tape that is slit from a wider prepreg to achieve finer control over the width of the tape, although overlaps and gaps between tapes can still be experienced. Due to the width of the feedstock the ATL machines are limited to flat or slightly curved parts (essentially single curvature) [5,6], whereas the AFP machines can cope with more complex doubly curved parts [7,8].

1.2. Quality control during layup

This paper will focus on the critical interaction between layup conditions and material quality prior- and post-layup. Processing conditions are identified that deliver a lay-up quality requiring the minimum of post-lay-up processing to achieve a high performance in the resulting cured laminate. A vital part of the cured quality is the level of voidage in the laminate [9]. Voidage can arise from multiple sources, such as moisture absorption and volatiles, but one critical source is air entrapment during lay-up. It has been shown that removing entrapped air from lay-ups is practically very difficult, with air permeability low in the fibre direction and essentially zero through-thickness [10–13], however it is often argued that a voidage below 2% by volume is necessary to achieve good mechanical performance and fatigue life in adverse service conditions [14].

For most modern prepregs, which possess a very low volatile content and water uptake, the final laminate void content principally depends on the amount of air that is entrapped during layup and the level of pressure that is applied during cure to collapse the entrapped air volume, see e.g. Ledru et.al. [15,16]. For relatively large parts this becomes even more critical as vacuum debulking may not be sufficient, due to the low permeability of the material, to remove air entrapped deeper inside the laminate. Manual lay-up of prepreg routinely uses regular debulking steps in which a vacuum bag is applied to the laminate and the laminate is held under vacuum for a period of time to reduce both air entrapment and the bulk factor, however debulking is often omitted in automated layup to improve productivity. Ideally, if the automated machines could eliminate debulking and deliver a lay-up that could be cured under a vacuum bag rather than requiring autoclave processing then significant savings in production time and capital expenditure could be achieved.

2. Simulator design

Preliminary studies [17,18] have shown that existing commercial layup systems have limited capability and relatively poor control over the conditions at the point of lay-down of the prepreg. It was therefore necessary to develop a laboratory based simulator rig [19,20] that would deliver prepreg under closely controlled conditions and also allow the delivery of prepreg under conditions outside the range of those available on the production machines used.

The simulator had to perform the basic functions of an automated layup system, which defined the major elements of the design, shown in Figs. 1 and 2 [20]. A diagram of the machine is given in Fig. 3. A rotary drive unit with an axis to mount 75 mm wide slit prepreg tape was fitted to the top of an Instron DX600 load frame. To control the temperature of the tape during layup an infrared heater was used. The prepreg was initially at ambient temperature, which was measured using a thermocouple, labelled B in Fig. 3. The heater temperature was measured using another thermocouple, labelled A in Fig. 3. Two pyrometers, labelled C and D in Fig. 3, were

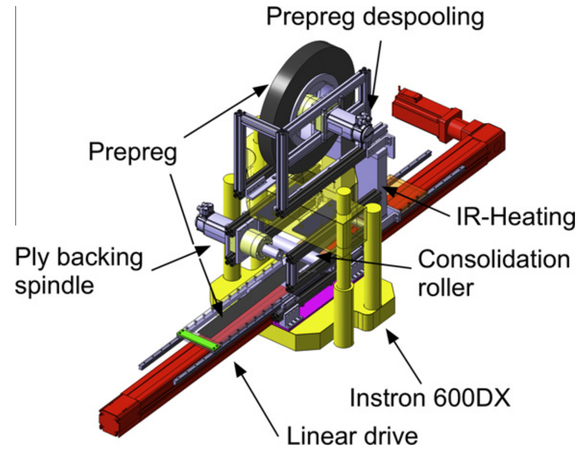

Fig. 1. Schematic lay-out of the simulation rig for automated layup.

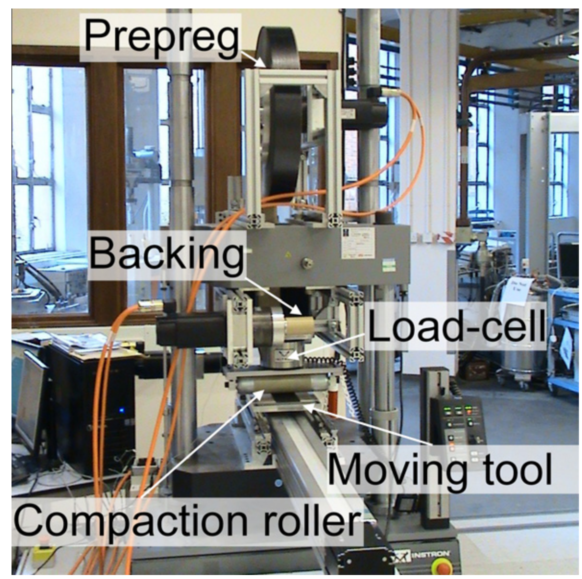

Fig. 2. Photograph of completed rig showing the major elements of the design.

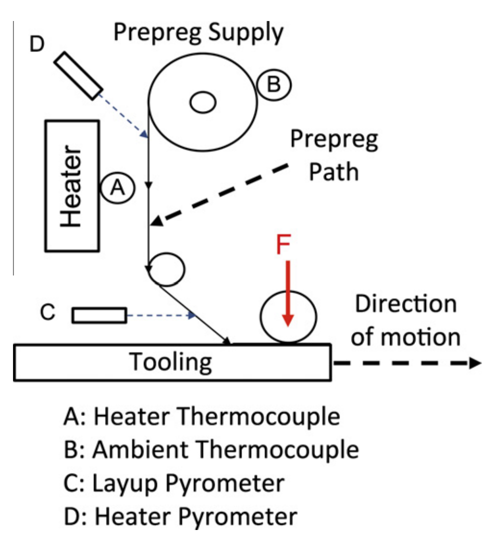

Fig. 3. Diagram of the machine operation and temperature measurements.