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ScienceDirect
Composites Science and Technology 67 (2007) 1892–1899
COMPOSITES SCIENCE AND TECHNOLOGY
www.elsevier.com/locate/compscitech

Effect of cure cycle heat transfer rates on the physical and mechanical properties of an epoxy matrix composite

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Received 11 August 2006; received in revised form 14 October 2006; accepted 14 October 2006
Available online 1 December 2006

Abstract

Although the autoclave technique produces composite parts of high-quality, the process is time consuming and has intrinsically high-capital and operating costs. Quickstep™ is a novel polymer composite manufacturing technique designed for the out-of-autoclave processing of high-quality, low-cost components with a reduction in cure cycle times. This paper assesses the use of the Quickstep method for the processing of an epoxy/carbon fibre aerospace material and compares this to equivalent composites produced using an autoclave process. Higher process ramp rates, achievable using Quickstep, have been shown to reduce resin viscosity thus facilitating void removal. Manipulation of the Quickstep cure cycle, while the resin is at low-viscosity, has significant effects on the mechanical properties of the product whilst simultaneously reducing the cure cycle time. Using Quickstep curing, samples were produced exhibiting comparable interlaminar properties but lower flexural strength as compared to those produced using the autoclave. However, normalisation of the data to a common fibre volume fraction showed that better interlaminar shear strengths could be obtained using Quickstep. This improvement in specific interlaminar shear strength was postulated to be due to the lowering of the resin viscosity over the duration of the cure, resulting in better wet through of fibres by resin and improved interfacial adhesion between fibre and matrix. This study identifies key parameters associated with the Quickstep process, providing a basis for further optimisation.

Keywords: Quickstep; A. Polymer matrix composites; B. Curing; B. Mechanical properties

1. Introduction

Advanced fibre-reinforced polymer composite materials have not been as widely adopted in industrial applications as would be predicted from their structural performance characteristics. The main reasons for their limited industrial use being the complexity of processing techniques and the associated high-production costs [1]. The use of advanced composites has, therefore, tended to be restricted to industries such as the aerospace and high-performance automobile industries accustomed to high-production costs and low-volume production.

Currently, high-performance composite components are predominantly produced by either hand or machine lay-up of prepreg laminates followed by treatment in an autoclave at elevated temperature and pressure using a programmed cure cycle. The high-pressure environment of the autoclave facilitates the dissolution and removal of voids present in the part, allowing the product to satisfy the stringent mechanical performance standards required by the aerospace and other high-performance industries. The removal of voids is of paramount importance since their presence can have detrimental effects on the mechanical properties of finished composite parts, manifested by a reduction in

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0266-3538/$ - see front matter © 2006 Elsevier Ltd. All rights reserved.
doi:10.1016/j.compscitech.2006.10.014

strength [2–5] and fracture toughness [6]. Additionally, the high-consolidation pressures involved in autoclave processing produces parts with high-fibre volume fractions which in turn leads to further improvement in mechanical properties [7]. Although the autoclave technique produces parts of high-quality, the process has intrinsically high-capital and operating costs. Additionally, to avoid resin exotherm runaway, the cure cycles employed for autoclave processing require relatively slow heat-up rates (1–4 °C min^{-1}) which, in addition to high-pressure generation (5–16 bar (500–1600 kPa)), result in time consuming procedures.

There has been a recent drive to develop alternative composite manufacturing technologies aimed at producing materials of similar quality to aerospace grade composites, but with shorter processing time and at a lower cost, e.g. vacuum film infusion [8,9], vacuum bag only processing [7,10] and electron beam curing [11]. In general, although non-autoclave techniques benefit from shorter process cycle times than autoclave curing, they tend to produce materials with inferior mechanical properties due to the absence of high-pressure.

Quickstep Technologies Pty Ltd. (Perth, Australia) has developed a novel composite manufacturing process, which can be utilised for the out-of-autoclave manufacture of advanced composite materials [12,13]. The Quickstep process utilises a fluid-heated, temperature controlled, balanced pressure, floating mould which takes advantage of the thermal conductivity of fluids. The process functions by rapidly applying heat to an uncured laminate stack; this is achieved by pumping a glycol based heat transfer fluid (HTF) over the part, thus encouraging convective heat transfer. The laminate stack is assembled on a single-sided mould tool using conventional lay-up; it is then sealed in a vacuum bag and transferred to a low-pressure chamber containing the HTF (Fig. 1).

Temperature control is maintained by continuously circulating the HTF through the pressure chamber. The mould and laminate stack are separated from the circulating HTF by two flexible silicone membranes. During processing of the composite, the HTF filled pressure chambers are clamped together. Owing to the balanced pressure environment, the closing of the pressure chambers permits the laminate to be compressed without subjecting the mould to any stress or distortion. The HTF also acts as a large thermal sink capable of removing any excess heat generated by exothermic resin curing reactions, allowing for the maintenance of a constant and well controlled temperature throughout the cure cycle of the laminate. The Quickstep process was described in detail by Griffiths [12] and Coenen [14].

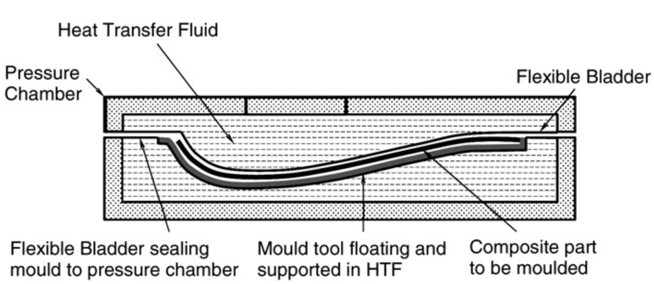

Fig. 1. Schematic of Quickstep process.

Liquids generally have thermal capacities greater than those of gases, thus the heat transfer rate between the HTF and laminate is much greater than that achievable in an autoclave; this leads to considerably improved heating/cooling rates and hence reduced cure schedule times. The higher heating rate allows a lower resin viscosity to be obtained in the laminate compared to autoclave processing thus consolidation is obtainable at lower applied pressures (typically vacuum, plus 10 kPa externally from the fluid). In addition, a lower viscosity improves the wetting of fibres by the resin matrix which has been demonstrated to increase fibre-resin adhesion and enhance mechanical properties [15–17]. Recent evaluation studies on the manufacture of a simple aircraft composite component have shown that the increased heat-up rate achievable using the Quickstep process improved its physical and mechanical properties as compared to composites produced using the autoclave process. Additionally, an 82% reduction in tooling and operating costs was achieved [14,18].

The aim of the current work is to manipulate the cure cycle used in the Quickstep process in order to modify the physical properties of laminates, whilst attempting to maintain mechanical properties rivalling those obtained when using high-pressure autoclave processes. The Quickstep process has the potential benefit of versatile production facilities with reduced capital outlay and faster cure cycles. Compared to autoclave methods, the reduced tooling and operational costs render the Quickstep process more attractive to the general composite industry.

2. Experimental

2.1. Materials

The composite system used in this study was Hexply 6376 prepreg (supplied by Hexcel Composites), comprising an epoxy resin/amine hardener matrix with unidirectional T800 carbon fibre reinforcement. 6376 is a prepreg system developed for autoclave cure and is primarily used in aerospace applications (typically close to 0% void content for autoclave cured panels).

2.2. Vacuum bagging

All cured composites were fabricated using a conventional vacuum bag lay-up, as illustrated in Fig. 2. Glass reinforced PTFE and Elastomax 224 nylon (supplied by Aerovac Systems) were used as release film and bagging film respectively. The breather fabric used was Ultraweave