Composites: Part A 52 (2013) 99–105

Contents lists available at SciVerse ScienceDirect

Composites: Part A

journal homepage: www.elsevier.com/locate/compositesa

The development of a high temperature tensile testing rig for composite laminates ☆

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A R T I C L E I N F O

Article history:
Received 15 November 2012
Received in revised form 30 January 2013
Accepted 15 April 2013
Available online 23 April 2013

Keywords:
A. Ceramic–matrix composites (CMCs)
B. Mechanical properties
B. High-temperature properties
D. Mechanical testing

A B S T R A C T

This study aimed to develop a high temperature tensile test capable of testing fibre reinforced composites up to 1000 °C, in order to understand the behaviour of certain composites at these temperatures and produce data suitable in the design of high temperature structures. The test design was assessed using finite element analysis before validating at ambient temperatures against conventional tensile test equipment. The chosen design achieved reliable tensile results and high temperature testing was then successfully conducted, using polysialate composite materials, establishing high temperature mechanical data which was previously unknown. The test setup and data achieved in this study are vital in the design of next generation high temperature structures.

1. Introduction

The recent resurgence and growing interest in high temperature structures to maximise design space and performance in aerospace and motorsport applications, has led to the need for greater understanding of high temperature composite materials. Fibre reinforced composite materials are typically required for their low weight and high mechanical performance, properties which are necessary for structural application. In addition to this, temperatures up to 1000 °C can be encountered, and as such, ceramic matrix composites are often sought [1]. However, the suitability of materials to perform in these environments is difficult to ascertain due to a lack of high temperature design data.

Mechanical property data is needed to understand the behaviour and limitations of composite materials at high temperatures, as well as allow accurate modelling to take place. Several mechanical tests are available to assess the mechanical properties of a material, of which tensile and flexural testing are the most common. Tensile testing is generally preferred to flexural testing, as flexural testing produces maximum stresses only in small regions at the test specimen surface, which can lead to localised effects. In addition to this, several failure mechanisms can be seen in flexural testing; tensile, compression and shear, which can allow more than one mechanism to dominate results. Tensile testing, however, produces maximum stresses throughout the test specimen as a whole, and the data achieved is more established and appropriate regarding the design and modelling of structures.

There are several components and aspects to tensile testing; the test coupon, grips and strain measurement are all required [2]. Typically tensile testing of composite materials uses hydraulic grips on flat rectangular samples, equipped with bonded end tabs to reduce stress concentrations and through thickness crushing. This is especially important with composite materials as they tend to be weak in the through thickness direction. However, the adhesives used to bond end tabs to composite coupons are only suitable up to a maximum of 300 °C. In addition to this, at temperatures up to 1000 °C attention is needed to both the gripping mechanism and material that the grips are constructed from. Strain gauges are usually employed to measure tensile strain, although these are typically bonded to the coupon, and the same problems with end tab adhesives arise. Therefore, high temperature tensile testing requires unique gripping, heating and strain measuring devices as well as an optimised specimen geometry, in order to successfully test tensile properties of composite coupons at high temperatures.

Current high temperature tensile test equipment is hard to source and typically impractical for use with thin composite laminates. Most available tensile test facilities with the ability to reach 1000 °C are designed for metallics with the use of cylindrical test coupons. Strain measurements are typically taken through the use of clip gauges, which can require notches in the coupon and can impart thermal stress concentrations. This study aims to provide a high temperature tensile test, suitable for thin, flat fibre

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http://dx.doi.org/10.1016/j.compositesa.2013.04.009

reinforced composite laminates. The use of thin coupons, approximately 1 mm, is required as it is representative of those used in structural applications and of the material thicknesses readily available for high temperature composites. In addition to this, there are several requirements that are sought to expand the ease-of-use of the test setup and drive the design. These include a simple, quick and cost effective high temperature tensile test, which makes use of small coupons to reduce cost, and where possible, integration into existing tensile equipment. The ability to add a high temperature capability to existing test equipment will add novelty to the test design as the majority of high temperature testing requires significant investment in both cost and time.

2. High temperature test method

The methods discussed for conducting high temperature tensile testing of fibre reinforced composite materials have highlighted the different approaches that can be taken. The requirements for this study stated that a simple, quick and cost effective high temperature tensile test should be chosen. In addition to this, thin, small coupons are needed due to the cost and availability of ceramic matrix composites, which are a focus of this test method. It is also advantageous for time and resource considerations to make use of existing and available test equipment where possible. With these requirements the most appropriate high temperature tensile test method was developed.

2.1. Grip design and test setup

After an extensive review of high temperature testing methods [2–6], hot passive grips, which grip the coupon through a wedge interference fit and apply edge loading, were selected as the most appropriate gripping technique. The coupon geometry is simplified and less manufacturing is required, as opposed to other methods such as pin grips, which require the drilling of several holes to the test coupon. This grip design can also be easily used with conventional servohydraulic tensile test machines available to this study. The grips will run hot, again to simplify the test procedure but also to remove thermal gradient problems associated with cold grips. In addition to this, the initial cost of the grips is lower than cold grips. This is because less manufacturing is required, as internal coolant networks are no longer necessary within the grip body, which also removes the need for ancillary pump systems to circulate the coolant. The use of hot grips demands that the grips be made from materials which retain sufficient strength at test temperatures. Nickel alloys, specifically Inconel 718 grade, have been selected as the most appropriate grip material for this reason. Although coupon test temperatures of 1000 °C were sought, only localised surface heating of the grips was observed at test temperatures during testing. This was due to the speed of coupon heating and the thermal mass of the grips themselves.

The grip design is similar to that used by Holmes [3] in the testing of SiC reinforced ceramic composites at 1200 °C. The grips comprise of the main grip attachment with an oversized cut-out for the coupon to be inserted, centreing inserts placed either side of the coupon once in the grip, retaining plates either side of the centreing inserts to reduce associated stress concentrations at the root from the coupon cut-out, and finally blinds to prevent the light produced by the rear emitter interfering with the optical strain measurement equipment. Misalignment of the coupon can cause significant bending stresses which can induce failure outside of the gauge section [3]. The centreing inserts reduce coupon misalignment and twist, keeping the coupon aligned between opposing grips, whilst also allowing lateral forces to be imparted on the coupon from the retaining plates. The use of the retaining plates to exert a degree of pressure laterally onto the centreing inserts and coupon face is important when testing thin coupons, as this mitigates any edge crushing effects on the coupon as the inserts are of the same material as the grip body. The grip assembly has been illustrated in Fig. 1, which shows the individual components discussed. Initial finite element analysis (FEA) of the grip setup indicated that significant stresses were developing at the root edges of the coupon cut-out. To reduce these effects the retaining plates were incorporated into the grip setup to reduce splaying of the cut-out forward edges, and as such, stresses at the root edges.

Heating of the coupon is conducted through an indirect heating approach, specifically infrared (IR) emitters. Several indirect heat sources could be used but short-wave IR emitters produced by Heraeus Noblelight Ltd. were chosen due to their small size and ability to reach temperatures as high as 2500 °C. In addition to this, a gold coating is specified on the back surface of the emitter so heat is typically radiated in one direction, minimising heating of other components and maximising the efficiency of the emitter. Initial testing of the test rig indicated that even at maximum emitter power the temperature of the rig and extended grip ends does not exceed 80 °C. In addition to this, the time required to reach uniform coupon test temperatures is typically between 1 and 2 min depending on the temperature sought. This is significant when comparing against conventional testing and heating methods which can require more than 60 min to achieve uniform temperatures. The thermal conductivity of the material tested also has an influence on the rate of heating, however, the use of thin coupons reduces this significantly, highlighting the effectiveness of the IR emitters and their placement within the setup. As heating of the coupon is through radiation, the high temperature capability of the emitters allows us to vary the power or distance of the emitters from the coupon and still achieve the test temperatures required. This extra flexibility in emitter placement is useful in the positioning of strain and temperature measurement equipment. Three emitters are used, placed either side of the coupon faces, allowing the test coupon to be seen from one side. The emitter setup is demonstrated in Figs. 1 and 2. The power of the emitters allows the setup to be unenclosed, which again provides easier access for strain and temperature measurement. Control of the emitters is by varying the power supplied to the emitters in order to achieve a specific temperature. Calibration is required to evaluate the appropriate power and the distance of the emitters to the coupon, to achieve the required coupon test temperature.

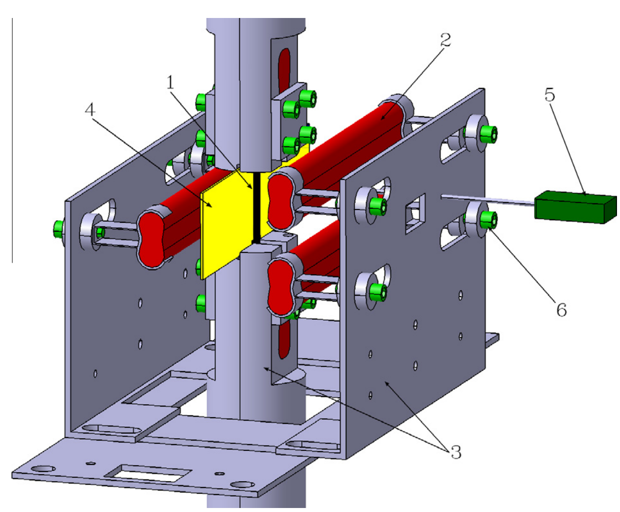

Fig. 1. Final grip assembly and test setup; coupon (1), three IR emitters (2), grips and rig (3), blinds (4), thermocouple (5) and bolts (6). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)