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Non-destructive evaluation of localised heat damage occurring in carbon composites using thermography and thermal diffusivity measurement

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A B S T R A C T

Carbon fibre reinforced polymer (CFRP) composites are now a common occurrence in the aerospace sector especially with their introduction into the aero-engine. With their ever-increasing use in harsh and extreme environments, it is important to understand their behaviour and performance when exposed to such working conditions. This paper presents a novel approach to understand the thermal degradation mechanism of CFRP composites based on the measurement of thermal diffusivity through non-destructive testing (NDT) when exposed to heat in a localised area. The study explored the suitability of pulsed thermography in detecting the physical damage caused due to localised heat exposure together with its ability to identify chemical change that occurs during the initial stages of exposure. The results showed the ability of thermography in detecting discolouration damage through the use of diffusivity measurements acquired by reconstructing the thermography dataset.

1. Introduction

The technological advancements in the area of advanced manufacturing over the last century have been a major driver for the introduction of advanced materials in the aerospace and automotive sectors. The aerospace industry has always been regarding the need for structural materials that are less dense, high in strength and are impact – abrasion – corrosion resistant. Carbon fibre reinforced polymers (CFRP) parts have now become the front runner due to their improved strength to weight ratio [1,2]. However, these composite materials are relatively new and their material properties are not fully defined. In fact, the earliest evidence of the introduction of CFRP in civil aviation applications came in the 70's with steady progress to specific application: such as primary airframe structure, in the late 90's [3]. Though these materials provide a better alternative to traditional metal counterparts, a number of limitations ranging from damage detection and characterisation for damage such as delaminations, disbonds, barely visible impact damage (BVID), water ingress and their repairability in service continue to be a challenge to the industry [4]. It must be understood that, the main reason for the uncertainty in the behaviour of the laminate with defects and damage under load is that fact that they are heterogeneous and anisotropic in nature and thus differ from their metallic counterparts.

1.1. Background

Literature indicated that the previous attempts to investigate damage created due to heat exposure was mainly in the 90's with more recent papers focussing on non-destructive evaluation (NDE) methods [5,6]. One of the major focuses of this paper is looking at the degradation process that occurs during the exposure of extreme temperature in a localised area and the laminates' response to such conditions. Research indicated that most of these studies look at uniform heat damage investigation with very limited information on the behaviour of CFRP when exposed locally [7–9]. Heat damage typically could occur as a result of fire or during service operations where they can be exposed to hot gasses, lightning strike, jet engine efflux during landing and exhaust from the jet engine [5,10]. Most of these degradations occur in localised areas and could go undetected. Thus, it is pivotal to understand and characterise such damage to prevent any catastrophic failure.

1.2. Heat damage

The damage created due to high temperature exposure on a composite material is referred to as heat damage and is a result of irreversible thermodynamic change that results in a physical and or chemical change. Studies have indicated that there are

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two major forms of damage which include incipient and physical damage [5,6]. Physical damage is characterised by various forms of cracks, disbonds, delaminations and blisters. They are created when the exposure temperature exceeds the materials glass transition temperature (T_g) [5]. On the other hand, incipient heat damage may not show any characteristic physical features that can be visually detected as they are created at a lower temperature exposure [10].

The damage creation is dependent on the selected heat source, the rate and amount of energy applied and the mode of application; conduction, convection or radiation [5,9,10]. In order to characterise damage, it is important to understand the impact of various factors such as material properties, impact of environment, the degradation process and the characteristic features of the damage created.

The performance of composites is primarily dependent on the material constituents such as the matrix composition, the type of resin and lay-up where the manufacturing processes determine the material characteristics of the laminate. Though the resin is non-conducting in nature, it can be understood that heat propagates through the fibres, them being conductive and thus their orientation and volume fraction control the thermal properties of the laminate, especially the carbon – graphene based composites [11,12]. Optimum curing is necessary as either under or over curing could result in a large variation in the laminates thermal property [13]. Studies indicate that moisture absorption over time is a major factor that contributes to environmental degradation where it alters the laminates durability leading to change in mechanical, chemical and thermo-physical properties [14]. With the presence of moisture, plasticisation can occur when exposed to extreme temperatures leading to permanent deformation. In addition to moisture, ultraviolet or UV degradation, foreign object contamination (chemical and biological), impact damage and fatigue are other environmental factors that affect the properties of CFRP laminates [14,15].

1.2.1. Thermal degradation process

There is significant evidence that the degradation attacks the matrix first, it being the most sensitive and reactive to heat and then the fibres [16–18]. On extended heat exposure, the resin starts degrading resulting in material oxidation and or pyrolysis which includes processes ranging from gas decomposition through to charring of the laminate [17].

Chemical degradation is mainly resin dominated and occurs before the formation of any physical damage such as cracks, blisters and delamination. Exposure to high temperatures results in depolymerisation, random chain scission, side group elimination and carbonisation of the composite. The initial exposure oxidises the matrix and can be characterised by a visible surface discolouration and is a result of cross-linking process that contributes to the release of volatile gases. Extended heat exposure further leads to charring as a result of resin pyrolysis [19,20]. It was reported that mass variation characterisation through Thermogravimetric Analysis recorded a mass loss due to volatilisation of the monomer confirming the loss of overall mass due to chemical degradation [21]. On the other hand, the physical irreversible damage is a result of rapid change through the glass transition temperature due to thermodynamic inequilibrium. It should be understood that thermal conductivity of the material plays a major role in the heat diffusion process especially during solidification and leads to change in the material density of the laminate creating free volume, residual mechanical stress and excess energy in the matrix [22].

1.2.2. Damage detection and characterisation using NDT

NDT techniques are those methods that determine the health of the component without causing further damage to the part being inspected [23]. As discussed, in the case of heat damage, NDT techniques such as thermography, ultrasonic testing and spectroscopy exist which provide an understanding of the damage occurring as a result of extreme temperature exposure [10]. Pulsed thermography has proven advantage of fast inspection with specific advantage of detecting defects and damage occurring in CFRP composites [24,25]. Studies also indicated that thermography and ultrasonic testing are not sensitive enough to detect incipient heat damage where there is minimal or no physical damage that is easily detectable with this technique with the diffuse reflectance infrared Fourier transform spectroscopy or DRIFT being the only other technique capable of monitoring chemical changes [5,10]. Where techniques like Fourier transform infrared spectroscopy (FTIR) are capable of detecting chemical damage, the ready and robust nature of pulsed thermography with additional suitability aspects such as large area ‘in-field’ inspection scenarios make it a more attractive alternative technology. The present study thus establishes the applicability of pulsed thermography in detecting discolouration damage through the use of surface diffusion measurements reconstructed from the acquired thermal data.

2. Methods & materials

This paper presents the research taken up to identify, classify and understand the characteristics of heat damage occurring in composites on a local area and presenting not just a damage creation method, but the establishment of a competitive technology to detect and establish incipient damage. For the scope of this study, a parametric experimental study was introduced to obtain repeatable and reliable results at the damage creation, damage detection and analysis stages. The local heat exposure was initially characterised by selecting a temperature range, based on the laminates response to the glass transition temperature of 195 °C and identified through numerous preliminary tests [26]. Based on the selected temperature range, multiple sets of experimentation were carried out to determine the effect of different exposure temperatures on degradation process over time. The following subsections clearly define the experimental specifications and plan.

2.1. Sample manufacture

For this study, HexPly M21/T800H unidirectional carbon-epoxy prepreg was chosen due to its good tensile strength of 2860 MPa and a high glass transition temperature of 195 °C [26]. The laminates were manufactured in a traditional autoclaving process to a quasi-isotropic layup to acquire 30 samples of $150 \times 100 \times 4$ mm. The sample thickness of 4 mm was selected based on the requirements for the short beam test as per the standard ISO 14130.

2.2. The experimental plan

Composite laminates post manufacture were carefully marked for repeatability and weighed to capture the weight after manufacture. They were then inspected for any surface inconsistencies and the same was recorded together with a pulsed thermography inspection of both sides of the sample. They were then exposed to localised heat using a hot air heat gun to achieve various levels of damage. The samples were subjected to visual inspection, pulsed thermography and was followed by ultrasonic immersion test to confirm damage. It should be noted that there was at least one ‘as-manufactured’ sample as a reference for all tests and 3 repeat samples with the same level of degradation were used for each test to achieve repeatability. Based on preliminary tests the following test routines were established;