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Thermal ageing effects on mechanical properties and barely visible impact damage behavior of a carbon fiber reinforced bismaleimide composite

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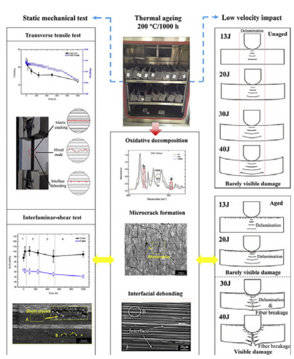
HIGHLIGHTS

- A C_f/BMI composite experienced high temperature exposure and remained favorable mechanical performance.
- Thermal ageing degraded static mechanical properties by inducing decomposition, interface debonding and microcracks.
- A modified C-scan technique was valid in determining efficiency of absorbed energy and impact failure mechanism.
- Thermal ageing enhanced critical transition from barely impact damage to visually detectable impact damage.
- Barely visible impact damage characteristics and corresponding mechanism of aged composite were revealed.

GRAPHICAL ABSTRACT



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ABSTRACT

Effects of ageing at 200 °C in air for up to 1000 h on static mechanical properties and low velocity impact behavior of a carbon fiber (T700) reinforced modified bismaleimide (BMI) composite have been investigated. A new C-scan data process method was applied to determine the variation in impact damage model and related failure mechanism due to thermal ageing, and attention was paid mainly to the barely visible impact damage. The transverse tensile strength and interlaminar-shear strength of the composite were found to decrease progressively with increase in ageing time, resulting from degradation of BMI matrix, damage of fiber/matrix interface and formation of microcracks caused by thermal ageing. It was shown that after thermal ageing, the impact damage model of the composite varied from a barely visible impact damage to a visually detectable impact damage as the impact energy reached the range from 20 J to 30 J. The employed C-scan data process method was proven to be more effective in revealing variation of impact failure mechanisms. It was deduced that the internal delamination dominated the barely visible impact damage model, and fiber breakage became more important in the aged composite as impact energy higher than 20 J.

1. Introduction

Carbon fiber reinforced polymer matrix composites (PMCs) are being used increasingly in the aeronautics and space industries, because of their high specific strength and modulus, low coefficient of thermal expansion (CTE) as well as other benefits [1,2]. Of all PMCs, the

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bismaleimide matrix composite is presently employed for commercial and military structural applications that involve long exposure to extreme conditions, and is also being evaluated for the next generation of civilian supersonic aircraft. As exposed to high service temperature, the long-term stability and corresponding ageing behavior of the BMI composite structures are of particular interest [3–6]. For example, the heating due to friction in air at surface of the aircraft during flight would have deleterious effects on mechanical performance of the composite and thus shorten the service reliability and lifetime.

The effects of thermal ageing on the static mechanical properties of the carbon fiber/BMI composite, including flexural strength, interlaminar shear strength (ILSS), fracture toughness and transverse tensile strength (TTS), have been recently investigated and significant variation in these mechanical properties was found [7–12]. The thermal ageing test is usually carried out at temperatures less than 250 °C in order to reduce testing time and fully assess the long-term performance of the carbon fiber/BMI composite under service condition. It has been found that serious charring began to occur on the surface of the carbon fiber/BMI composite as the temperature around 250 °C [7]. The mass loss, variation in glass transition temperature (T_g) and chemical structure of BMI matrix along with formation of microcracks and debonding of fiber/matrix interface, induced by thermal ageing, were considered to be responsible for the mechanical property variation [8–12]. However, up to the present, the opinions about the thermal ageing effects on static mechanical properties of the carbon fiber/BMI composite are inconsistent. Xingying Lv et al. [8] found that the flexural strength of a carbon fiber-reinforced BMI composite increased after being aged at 150 °C for 1100 h, and they attributed it to the post-curing of BMI resin during thermal ageing. On the other hand, Mohammad et al. [11,12] revealed that the flexural strength of another carbon fiber-reinforced BMI composite decreased after subjected to an isothermal ageing at 260 °C in air for nearly 3000 h, which was thought to result from the formation of microcracks, fiber/matrix interface debonding during thermal ageing. The main reason of this inconsistency lies in that the thermal ageing effects are complicated and related to characteristics of the carbon fiber/BMI composite and the ageing conditions such as atmosphere, temperature and time.

In addition to static or quasi-static mechanical properties, the aeronautics engineers also pay particular attention to the low velocity impact performance of PMCs. Many typical aircraft structures such as fuselages, tails and wing skins, are vulnerable to foreign object impact, including drop of handle tools, impact of small debris on runway or flying fragments during flight, which might result in significant internal damage and cause remarkable loss of residual strength and service lifetime [13–15]. Matrix cracking, delamination, fiber breakage and interface failure are the typical damages occurred in PMCs under low velocity impact [16,17]. It has been reported that the characteristics of matrix and fiber, fiber orientation and volume fraction, fiber/matrix interface and frequency of loading all have obvious influences on the low velocity impact behavior of PMCs [18,19]. Meanwhile, some researchers made great efforts to evaluate the environmental factors such as temperature, moisture and UV rays on impact damage behavior of the PMCs for the consideration of service in harsh environments [20–23]. Wei Fan et al. [21] examined thermal ageing effects on the maximum impact contact force (F_{max}) of a carbon fiber/epoxy composite exposed at 140 °C for up to 1200 h. It was indicated that the F_{max} of the composite decreased with increasing ageing time due to degradation of the epoxy matrix and carbon fiber–epoxy interface, which might hide huge safety danger for practical application. Akay et al. [23] used the Charpy test method to investigate the effects of long-term high temperature exposure on impact performance of a carbon fiber/BMI composite, and it was found that the failure model of the composite experienced a variation from a brittle failure to a progressive delamination after ageing at 230 °C. On the other hand, the drop weight impact test method was employed more extensively by other researchers who regarded it as a more representative approaches for assessing the impact response of PMCs [24].

Although considerable experimental works have been carried out on impact behavior of PMCs and their structures, there are limited studies particularly focused on the barely visible impact damage. Such damage is not visually detectable and would reduce strength of the composite significantly and cause catastrophic failure suddenly in low velocity impact event. And the investigation on the effects of thermal ageing on low velocity impact behavior of thermoset resin matrix composites, as evaluated by drop weight test, is really rare, especially in the case of carbon firber/BMI composite. Reminding of the fact that one major disadvantage of carbon fiber/BMI composite is its high susceptibility to the damage in the form of interlaminar delamination which is frequently encountered under low velocity impact and barely visible detected, it is essential to investigate the influence of long term exposure to high temperature on low velocity impact behavior of carbon fiber/BMI composite which is going to be applied with any confidence.

The purpose of this study is to evaluate the thermal ageing effects on the static mechanical properties and low velocity impact performance of a carbon fiber reinforced modified BMI composite (T700/HT280 BMI) proposed for aerospace applications. The composite was firstly aged at 200 °C in air for various times up to 1000 h and the drop weight impact test was then carried out to simulate actual impact by a foreign object at low velocity. A variety of impact energies were applied to induce different type impact damage in the composite. The characteristics of barely visible impact damage were investigated, the critical visible impact damage energy-E_v was identified and the corresponding impact damage mechanism variation of the composite after thermal ageing at 200 °C was also discussed. Additionally, considering the limitation of traditional C-scan technique, a modified C-scan data process method was employed to estimate the relevant impact damage. The outcomes of current study might provide beneficial information for aerospace engineers.

2. Experimental

2.1. Material and specimen preparation

In this study, a carbon fiber (T700) reinforced a modified BMI (HT280) resin composite is used as the experimental material. The T_g of the HT280 BMI resin was determined as 318 °C by DMA analysis technique. This T700/BMI composite is primarily proposed for the production of load-bearing structures served at temperatures as high as 204 °C in aerospace industry. Two types of layup, unidirectional (Com1) and multidirectional [0/45/−45/90/0] (Com2), were utilized for investigation. Subsequent laminated panels were manufactured using prepreg with HT280 BMI reinforced by T700 carbon fibers with a fiber volume fraction of 60% ± 2%. The laminates were individually cured in an autoclave, utilizing standard aerospace cure cycles as presented in Fig. 1. The quality of the laminates was detected and evaluated using an ultrasonic C-scan technique. The seams of each panel were offset by 10 mm to prevent the creation of weak areas and then the panels were cut into specimens. The corresponding geometric details of specimens are tabulated in Table 1.

2.2. Thermal ageing

The composite components exhibit continuous service temperature resistance up to 204 °C. The ageing temperature (i.e. 200 °C) was chosen to represent the aerodynamic heating at the surface of the aircraft (≤180 °C), taking into account both limit on accelerated-ageing conditions and high-temperature service environment of the composite (170 °C–204 °C) as well. Specimens were dried in a vacuum oven at 70 °C under until a constant weight was achieved before ageing in air-circulating oven at 200 °C for various periods of time up to 1000 h. After removal from the oven, the specimens were allowed to cool to room temperature in a desiccator.