Cold Regions Science and Technology 96 (2013) 8–16

Contents lists available at ScienceDirect

Cold Regions Science and Technology

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

Ice adhesion to pristine and eroded polymer matrix composites reinforced with carbon nanotubes for potential usage on future aircraft

Omid Gohardani *, David W. Hammond

Department of Power and Propulsion, School of Engineering, Cranfield University, MK43 0AL, United Kingdom

ARTICLE INFO

Article history:
Received 2 January 2013
Accepted 4 September 2013

Keywords:
Aircraft icing
Future aircraft
Carbon nanotubes
Buckypaper
Composite materials
Icing tunnel

ABSTRACT

In aircraft icing conditions, the accretion of super-cooled liquid droplets on to the surface of an aircraft is dependent on numerous factors. In particular the temperature, liquid water concentration and material properties are of crucial importance in this context. This article features results obtained upon accretion of impact ice on pristine and eroded polymeric matrix composites with and without carbon nanotube reinforcement, for potential use in aeronautical applications. Results are shown for ice shear strength of a selection of advanced materials at $T = -5$ °C and $T = -10$ °C for a liquid water concentration $LWC \cong 0.3\ g \cdot m^{-3}$, actualized in an icing tunnel. The effect of surface roughness is further examined on the considered specimens in relation to their ice shear strength characteristics.

1. Introduction

Ice accretion on different surfaces can ensue in undesired loads in particular on power lines, wind turbines, dams and telecommunication apparatus (Frankenstein and Tuthill, 2002; Varanasi et al., 2010). In aeronautics, the influence of aircraft icing and ice accretion has been recognized as early as in 1920s (Leary, 2002) due to the detrimental effects that these may have on an aircraft. For this reason the influence of ice adhesion on various surfaces of aircraft, missiles and helicopters has continuously been studied in the aerospace industry. In particular, the emerging development of advanced composite material and their usage within the aeronautical industry has sparked the interest for research on ice adhesion characteristics of materials that are icephobic, i.e. on which ice minimally adheres (Gohardani, 2012a). Although commonly special fluids and sacrificial coatings are utilized within the aerospace industry, the environmental impacts of utilizing such means have generated an interest to further pursue the search for icephobic coatings (Meuler et al., 2010). The advantages of utilizing icephobic materials are evident upon the aerodynamic benefits attained during flight and minimization of de-icing usage prior to flight which results in a more environmental friendly approach.

The choice of adequate materials to be utilized on an aircraft is highly complex due to their demanding environmental exposure that may constitute hazards such as atmospheric conditions, erosion and weathering, lightning, and foreign object damage (FOD) (Gohardani, 2011a). An appropriate approach for identification of adequate specimens, is hence to consider established materials and subject these to constituency modifications in order to obtain more advanced characteristics. In the present study, a set of established materials utilized in the aerospace industry are subjected to reinforcement with multi-walled carbon nanotubes. Studies conducted by Gohardani and Hammond (2011, 2012, 2013) have indicated that the same specimen set reinforced with multi-walled carbon nanotubes (MWCNT) has exhibited a more hydrophobic nature in relation to the pure resins.

The formation and adhesion of ice on space vehicles have also been subjected to several investigations by other researchers (Deweese et al., 2006; Ferrick et al., 2006a,b). In particular for space applications, the interest for finding suitable substrate materials, stems from the debris of ice that may form during the launch of future space shuttles and potentially damage the external surfaces of these vehicles. Further, the release of ice under gravity at a moderate speed is preferred as it ensues in a lower damage potential. A challenging task in space applications is that the desired coating should remain icephobic when operating in cryogenic temperatures.

An important property in aircraft icing applications is the inherent ice adhesion characteristics of the materials utilized on the various surfaces of the aircraft. It is often desired that the utilized materials have low ice adhesion strength, enabling them to easily detach from the surfaces of the aircraft. Empirical studies of the ice adhesion strength for different materials are intricate for dynamic settings during which the ice accretion is in process. Hence, most researchers revert to static methods in which the ice is removed from the surface by means of pushing/pulling (Murase and Nanishi, 1985). A more dynamic approach is to utilize the rotational system in which the shedding of the ice is attained by the outward pushing force of the apparatus (Kulinich and Farzaneh, 2009). Since a more realistic approach is to utilize an icing

* Corresponding author.
E-mail addresses: omid.gohardani@alumni2009.cranfield.ac.uk, omid.gohardani.cranfield@gmail.com (O. Gohardani).

0165-232X/$ – see front matter © 2013 Elsevier B.V. All rights reserved.
http://dx.doi.org/10.1016/j.coldregions.2013.09.005

Nomenclature

τ_{ice}	ice shear strength [MPa]
CNT	carbon nanotubes
FOD	foreign object damage
h_{ice}	thickness of accreted ice [mm]
H	height, thickness [mm]
HMEM	high mechanical energy mixer
HSM	high shear mixer
L	length [mm]
LWC	liquid water content [$g \cdot m^{-3}$]
M	Mach number
MVD	median volume diameter [μm]
MWCNT	multi-walled carbon nanotubes
$\hat{P}$	peak pressure [MPa]
P_a	air pressure [psi]
P_s	threshold pressure [MPa]
P_w	water pressure [psi]
R_a	surface roughness [μm]
S_n	specimen number n
T	temperature [°C]
U_∞	free-stream velocity [$m \cdot s^{-1}$]
W	specimen width [mm]

tunnel in which the flight conditions are replicated and the accretion and adhesion of ice are natural, the Cranfield Icing Tunnel located in United Kingdom, was utilized in this study for ice adhesion tests on the considered specimens in two different surface finish conditions. The pristine and eroded states of the material specimens, were used in order to examine the effect of wear and erosion on the accretion and adhesion characteristics of the considered materials. In light of this discussion, the given specimens were subjected to ice shear tests by means of a designed ice adhesion unit (Gurrutxaga Lerma, 2010; Lou, 2009; Moncholi Piles, 2011; Pervier, 2009; Terzis, 2009).

2. Experimental specimens

A total number of 10 different materials referred to hereafter with a specimen number S_n, with $n = \{1,2,\ldots, 10\}$, were utilized in this study. Specimens S_1–S_8 were supplied in two different prescribed conditions, namely as supplied and in an eroded condition. Specimens S_9–S_{10} were only examined in the pristine state, since they both featured the gelcoat SW404 as the surface layer. The majority of the considered materials were established epoxy resins commonly used within the aerospace industry with the addition of carbon nanotubes as a reinforcing agent. Table 1 provides an overview of the utilized specimens.

2.1. LY564 (S_1)

The LY564 supplied by Huntsman had the epoxy component, Araldite® LY564 and hardener Aradur® 2954 both in liquid form, without any nanofillers. The epoxy was mixed with the hardener by mechanical stirring at 20 rpm for a period of 15 min. Curing cycles of 1 hour 80 °C and 8 hour 140 °C were employed for preparation of this specimen.

2.2. LY564 + 0.5% MWCNT (S_2)

The LY564 + 0.5% MWCNT sample was the nanocomposite of the LY564, consisting of the epoxy component Araldite® LY564 and hardener Aradur® 2954 in liquid form. The nanofiller in this material was 0.5% of the weight of MWCNT, Graphistrength® C100, from Arkema. The length of the MWCNT was 0.1–10 μm, with the outer mean diameter of 10–15 nm and a mean agglomerate size of ~200–500 μm. Initially, a masterbatch consisting of a 3.45 wt.% MWCNT was prepared by means of a Heidolph RGL stirrer and a Cowles disk operated at 5,000 rpm for 15 min. Upon dilution of the masterbatch with the neat epoxy, an EXAKT 80E three-roll mill was employed for processing of the mixture by calendering. The used feed roll, center roll and apron roll were set to 17 rpm, 50 rpm and 150 rpm, respectively. Upon feeding the mixture into the three-roll mill and shearing for 2 min prior to collection, the entire collected volume was passed-through the mill at progressively smaller gap settings between the rolls. The collected epoxy and carbon nanotube dispersion were thereafter mixed with Aradur® 2954 by mechanical stirring at 20 rpm. The employed curing cycle for this specimen was similar to that of the pure resin.

2.3. 32-MINAS1-06 (S_3) and 32-MINAS1-07 (S_5)

This bi-component epoxy resin system, consisted of an Araldite® MY0510 epoxy in liquid form and an Aradur® 976-1 hardener in powder form, without a nanofiller. The mixing of the components was carried out in accordance with 100 parts A and 62 parts B based on weight mix-ratio, followed by mechanical stirring under vacuum during 30 min at 20 rpm. Upon casting in a metallic mould, a curing process in an oven was executed in two 30 min cycles at 80 °C and 100 °C, followed by two 90 min cycles at 120 °C and 150 °C, and a final 120 min cycle at 177 °C.

2.4. 32-A05-CANBIO1-06 (S_4) and 32-A05-CANBIO1-07 (S_6)

Similar to the pure resin, this specimen consisted of an epoxy component Araldite® MY0510, in liquid form and a hardener Aradur® 976-1, in powder form, with 0.5 wt.% MWCNT Graphistrength® C100, supplied by Arkema. The dispersion process for the masterbatch consisted of an initial mixture of the epoxy and 2 wt.% carbon nanotubes. Homogenization of the mixture was achieved by using a high shear mixer (HSM) at 6000 rpm with a duration of 30 min and a subsequent dispersion improvement using a high mechanical energy mixer (HMEM). In the sampling step, the duration of HMEM employment was optimized with respect to mechanical energy and mixing

Table 1
The notation, resin and hardener, and the corresponding reinforcement when applicable.

Notation	Resin and hardener	Reinforcement
S_1	Araldite® LY564†	None
	Aradur® 2954†	
S_2	Araldite® LY564†	0.5 wt.% MWCNT
	Aradur® 2954†	Graphistrength C100
S_3	Araldite® MY0510	None
	Aradur® 976-1	
S_4	Araldite® MY0510	0.5 wt.% MWCNT
	Aradur® 976-1	Graphistrength C100
S_5	Araldite® MY0510	None
	Aradur® 976-1	
S_6	Araldite® MY0510	0.5 wt.% MWCNT
	Aradur® 976-1	Graphistrength C100
S_7	Araldite® DBF	10 wt.% AlN
	Aradur® HY956EN	
S_8	SW404	None
	XB5173	
S_9	SW404	Buckypaper
	Araldite® MY0510	5.5% MMT
	MTM44-1 FR	
S_{10}	SW404	5.5% MMT
	Araldite® MY0510	
	MTM44-1 FR	