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Evaluation of commercially available materials to mitigate insect residue adhesion on wing leading edge surfaces

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ABSTRACT

Surface contamination from insect strikes on aircraft wing leading edges can induce localized boundary layer transition from laminar to turbulent flow, resulting in increased aerodynamic drag and reduced fuel efficiency. As aviation fuel costs continue to climb, strategies to reduce fuel burn using laminar flow have led to renewed interest in surface modifications to minimize the effects of insect residue adhesion on aircraft wings. Under NASA's Environmentally Responsible Aviation Program, insect residue adhesion-resistant coatings are being studied as an approach for drag reduction. A series of aluminum alloy test surfaces were coated with commercially available materials and characterized using contact angle goniometry. The surfaces were subsequently subjected to controlled impact of crickets using a custom-built pneumatic insect delivery device. Impact events were recorded and analyzed using high-speed digital photography and characterized using optical surface profilometry. Residue adhesion was observed on all of the coatings investigated. The cricket impact event was related to liquid droplets impacting surfaces at high velocities and was analyzed as such. Coating surface energy was determined to influence residue adhesion.

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1. Introduction

Laminar flow is the smooth, uninterrupted flow of air over the contour of wings, fuselage, or other parts of an aircraft in flight [1,2]. Maintenance of laminar flow during cruise may become an operational necessity for future fuel-efficient aircraft configurations [3]. Laminar flow can be maintained in the stream-wise direction on an aircraft wing either passively through natural laminar flow induced by the shape of the airfoil, actively by laminar flow control through perforations on the airfoil that can introduce suction or by hybrid laminar flow control which combines the two approaches. Factors that can destabilize a laminar boundary layer and cause transition to turbulent flow include adverse pressure gradients, surface roughness, heat and acoustic energy [1–3]. In the case of surface roughness, the critical height of a topographical imperfection that induces transition from laminar boundary layer flow to turbulent is dependent on the airfoil and Reynolds number and can be as small as several microns [2]. Flight tests have shown that insect strikes on wing leading edge surfaces can leave residue exceeding the critical heights sufficient to disrupt laminar flow and decrease fuel efficiency [1–3]. These residues have long been recognized to adhere to exposed aircraft surfaces [1–25]. In fact, the drag coefficient measured on an aircraft wing was determined to increase as much as 100% according to a study published in 1950 [22]. Studies have shown that airborne insect densities are greatest between ground level and 153 m, with the highest insect population present during conditions of light winds (2.6–5.1 m/s), high humidity, and temperatures ranging from 21 to 29 °C [26,27]. As a consequence, aircraft are most susceptible to insect strikes during taxi, takeoff, initial climb, approach and landing. Similarly, insect debris can influence the efficiency of wind turbines as was recently reviewed [28].

The development of surface roughness from insect strikes involves numerous complex chemical reactions. In general, an insect consists primarily of an exoskeleton and hemolymph (i.e., blood) [3]. Upon impact with a surface, the exoskeleton ruptures and releases hemolymph that can subsequently spread. Once activated by this injury, phenoloxidase and hemocytes present in the hemolymph become very sticky adhering to glass, plastic, and other materials [29,30]. These activated "glue" components remain on the impacted surface and promote adhesion of exoskeleton parts, most of which can exceed the critical surface roughness height and

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induce localized boundary layer transition on a wing leading edge. A comprehensive review of the relationships between airflow, insect strike location, and the resultant insect residue heights was published by Coleman in 1961 [27]. Based on Coleman's report, and other literature sources, impacts from insects during air travel are most likely to occur on the leading edge and immediately surrounding area of an aircraft wing. Thus, natural laminar flow would be interrupted, diminishing fuel burn rate improvements arising from airfoil shape as well as negating further efficiency improvements from hybrid laminar flow systems.

Numerous approaches to mitigate insect residue adhesion on the wing leading edge surface have been investigated over the past 60 years. The easiest and most economical relied upon natural erosion of insect residue through a combination of air temperature, flight speed, and moisture provided by flying through clouds. This approach however is too condition-dependent to be reliable [5,8,12,14,15,19]. Hardware-based solutions have included mechanical scrapers [4,5,8,14], deflectors [6,8,9,14,16,18,20,23,24], paper and/or other coverings [1,2,8,13,14,22]. While these technically solved the problem, the approaches were either difficult to implement and/or necessitated a weight penalty preventing implementation on a commercial scale. The Krueger flap is a deflector designed to improve lift for large aircraft (e.g. Boeing 737 and 747) during takeoff [2]. Although it has been shown to negate insect residue from the wing leading edge so as to retain laminar flow on the upper wing, physical discontinuities of the flap may induce early boundary layer transition on the lower wing surface.

Physical and chemical modifications to the wing leading edge surface have been investigated including elastic surfaces [25], coatings [12,19,21], soluble films [7,8,16,24], and fluid covers [8–12,16,17,19]. Elastic surfaces were found to work well with minimal traces of insect residue, but rain erosion and hail were a concern due to potential damage to the surface [25]. Soluble films such as glycerin provided a good barrier to insect residue adherence to the wing surface and could be easily washed or blown away taking the insect residue with it [7,8,16,24]. Problems with this strategy were that it was only useful upon takeoff, had to be applied prior to every flight, and if the film did not provide complete coverage (i.e. wetting) over the wing then insect residue would stick to the non-wetted wing surfaces. Fluid covers formed through a continuous liquid discharge from the deicing system were successful in preventing a majority of insect residue from adhering to the surface; however, it was only effective when turned on [7–12,15,17,19]. Besides coverage and environmental concerns, weight and economic penalties associated with transporting the fluid necessary for the portions of the flight profile where insect strikes are a problem as described above could be problematic, as well as complete coverage of the wing surface by the fluid as previously mentioned.

Coatings offer an advantage over previous strategies due to ease of application, potentially negligible weight penalty, reduced environmental concerns, better economics, and continual function throughout the flight profile [12,19,21,31,32]. Hydrophobic and superslick coatings for insect residue mitigation have been flight tested. It was determined that Teflon® based coatings and other coatings based on products in use at the time on airplane windshields and radomes to repel rain were ineffective in mitigating insect contamination [12,19]. However, residue was reported to be easier to wipe off from Teflon® based surfaces compared to other coatings after the flight test. A non-flight coating study evaluated surface energy and roughness effects of various polymer films on aluminum (Al) alloy substrates toward insect residue adhesion [21]. The coatings were NyeBar®, poly(methylmethacrylate), Udel® P-1700, and Teflon®. Insect strikes were obtained via a jig mounted on an automobile. Although insect residue was observed on all surfaces, those with lower surface energy exhibited less spreading of the residue.

The current study evaluates the influence of coating surface energy on insect residue adhesion. Single insect strikes were achieved using controlled delivery from a custom-built pneumatic insect delivery device. This approach affords a representation of the dynamics involved in flight enabling development of a scientific understanding of the problem and identification of potential solutions. Several materials were selected that represented different chemical functionalities and hence surface energies. Although the exact compositions of the commercial-off-the-shelf (COTS) materials used here were not available, the general chemical compositions were discerned from the corresponding material safety data sheets. The chemistries evaluated in this work included an aliphatic, fluorinated polymer (NyeBar® Type L), substituted polysiloxanes (COTS 1 and COTS 2), poly(vinyl alcohol) (COTS 3), a fluorinated silane-coupling agent (Hydrophobic), an ethylene glycol containing silane-coupling agent (Hydrophilic), and a hydroxyl-functionalized methacrylate (pHEMA). Fluorinated and siloxane based materials are known to possess low surface energies and were selected based on results from previous studies [12,19,21]. COTS 3 was selected based on advertisements promoting ease of insect removal using a water wash. The Hydrophilic material was chosen based on a report that glycols were good solvents for insect proteins [17]. pHEMA was selected based on its report as an adhesion inhibitor for insect hemocytes [31].

2. Materials and methods

2.1. Materials and chemicals

Materials used in this study included eight different coatings applied to Al alloy substrates and natural and synthetic insect hemolymph. Sheets of an aluminum/silicon (84/16) alloy were obtained from commercial sources. The Al alloy substrates (approximately 18 cm × 10 cm × 102 μm) were wiped with ethanol using a dust-free laboratory cloth prior to surface treatment or analysis. Commercial-off-the-shelf (COTS) coating products were purchased from national retail chains for testing. These materials, referred to hereafter as COTS 1–3 were applied per manufacturers' instructions. The formulations of COTS 1 and 2 are based on proprietary siloxanes and COTS 3 is based on poly(vinyl alcohol), as deduced from material safety data sheets. Heptadecafluoro-1,1,2,2-tetrahydrodecyltriethoxysilane (referred to as Hydrophobic) and 2-methoxy(polyethyleneoxy)$_{9-12}$propyl trimethoxysilane (referred to as Hydrophilic) were purchased from Gelest, Inc. and used as-received. These silane-based materials were applied by spray coating of 1–2 wt% aqueous ethanol solutions after acid hydrolysis with glacial acetic acid. Another sample was generated with a combined application of the Hydrophobic and Hydrophilic materials (approximately 1:1 ratio) and is referred to as Mixed. Poly(2-hydroxyethyl methacrylate) (pHEMA) was purchased from Sigma Aldrich and applied by spray-coating a 1–2 wt% ethanol solution. NyeBar® Type L was purchased as a 0.2 wt% solution from Tai Lubricants and applied by spray coating. Grace's insect medium was obtained from Sigma Aldrich and used as-received. Bait crickets (*acheta domestica*) were purchased from Wilcox Bait and Tackle Shop located in Newport News, VA.

2.2. Contact angle goniometry

Contact angle goniometry was performed using a First Ten Angstroms FTA 1000B goniometer. Sessile drop contact angles were measured for each sample using a 5 μL drop of either water or ethylene glycol, or a 2 μL drop of methylene iodide. Interfacial tension