LABORATORY TESTING OF INSECT CONTAMINATION FOR LAMINAR FLOW APPLICATIONS USING AN INSECT-IMPACT TEST FACILITY

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Keywords: *insect contamination, laminar flow, coatings*

Abstract

The effectiveness of drag-reducing laminar flow technologies can be limited by insect contamination on aircraft leading edges. Test equipment was developed to study insect impact events. The adhesion of Drosophila Melanogaster to five low-surface-energy coatings was evaluated (insect residue height and area were determined) and compared to measured surface energies and surface roughness. The dominant factor influencing the rupture speed (i.e. the lowest speed needed to fracture the exoskeleton) was seen to be the orientation of the insect body relative to the surface on impact.

1 Nomenclature

h_{crit} critical height to transition
γ_s surface free energy
γ_s^p polar component of surface free energy
γ_s^d dispersive component of surface free energy

2 Introduction

This study addresses insect contamination on aircraft leading edges, with an application to drag-reducing laminar flow technologies. The specific objectives were to

(a) Design and manufacture two bespoke pieces of experimental equipment (test rigs), capable of impacting insects onto test coupons at speeds up to 100 ms^{-1}; and
(b) Evaluate the ability of alternative coatings to prevent or reduce the adhesion of crushed insect bodies when subjected to high-speed impact.

Insects striking the leading edge of laminar flow surfaces – where the laminar flow is achieved by either Natural Laminar Flow (NLF) or by Laminar Flow Control (LFC) – has long been recognised as one of the most significant problems associated with the commercial exploitation of NLF or LFC technologies. The threat of contaminating the laminar flow surface is almost entirely confined to aircraft operations in close proximity to the ground – typically below 500 ft [1] – and requires mitigation during associated flight phases. If the speed of impact is sufficiently high, the insect's exoskeletal cuticle will rupture and the haemolymph (blood), which is then released, will act as glue, binding parts of the broken insect body to the aircraft's skin. Studies conducted by Coleman (1961) [1] concluded that an impact speed of about 10.9 m/s was sufficient for this to occur (using the same insects as the current study – Drosophila Melanogaster). The minimum rupture speed depends on the mass and anatomical structure of the insect, in particular the toughness of the cuticle.

The amount of insect matter or residue that remains on the surface is seen to depend on several factors, including the characteristics of the leading edge skin material (e.g. surface free energy, surface roughness, rigidity), insect impact angle and speed, ambient conditions (e.g. temperature, humidity, air flow over the impact site), and insect type.

An important parameter for laminar flow is the resulting height of the insect residue, as laminar–turbulent transition of the boundary layer will occur if the height exceeds a critical excrescence height ($h_{\mathbf{crit}}$) for the flow conditions at the impact site. The critical height is considered to be a variable, depending on the Reynolds number, the stability of the boundary layer (this implies that the chordwise position of the impact site on the wing is important) and even on the presence of outer flow disturbances.

The critical height of a roughness element (excrescence) that will trigger transition has been the subject of many laboratory and flight investigations since the 1950s [1–4]. In parallel, field studies have been conducted in an attempt to quantify the threat posed by insects and the nature of the resulting impact residue [5–7]. There is also evidence that subsequent flight through rain or hail tends to clean the aircraft's surface, removing insect debris and leaving residues of a reduced height [8–10]. This influence, however, has proven to be difficult to quantify.

There have been many prior attempts to solve the problem of insect contamination disrupting laminar flow, involving both preventative methods (e.g. by employing a shield [11–12] or by wetting the surface [13]) and cleaning methods (e.g. by using enzymes that will actively degrade the adhesion of the insect matter to the skin [14]). Many of these ideas, interestingly, are described in the early work of Coleman [1]. Despite the broad range of concepts that have been investigated [15], the fact remains that the majority of these ideas are impractical for operational aircraft. Modern low-surface-energy coatings, however, provide an exciting opportunity to re-address this issue, but they are not without their problems: many are not sufficiently durable to survive the harsh, abrasive environment encountered at the leading edge of high-speed aircraft wings.

The current study is being conducted as part of the European Union (EU) sponsored FP7 project AEROMUCO (AEROdynamic surfaces by advanced MUltifunctional COatings). This project aims to "develop and evaluate a number of alternative – and highly innovative – active and passive multi-functional surface protection systems for future generation of aircraft, leading to a significant improvement in fuel efficiency" [16].

In the work herein reported experimental equipment (i.e. laboratory test rigs) has been developed at the University of Limerick (Ireland) specifically to study insect impact events (Section 3). Insect adhesion to a number of low-surface-energy coatings has been investigated – Section 4 describes the experimental procedure and Sections 5 and 6 record and discuss the results obtained to date.

3 Insect impact test rigs

3.1 Overview

The testing of anti-contamination coatings to insect adhesion is a non-trivial exercise: there is no standardized test equipment, nor standard test methods. At the University of Limerick, two test rigs – each employing a different test principle – have been developed. The first concept involves accelerating an insect (or insects) towards a stationary test coupon. This test rig is known as the *Stationary samPle Insect Impact Test* (SPIrIT).

The second concept involves accelerating a test coupon (supported within a holder) towards a quasi-stationary insect (or insects). This test rig is known as the *Accelerated Sample insecT Impact Rig* (ASTIR). The SPIrIT rig includes more variables as it is operated in an open laboratory with air currents and temperature changes that can affect the trajectory and velocity of the insect(s). The ASTIR has the benefit of the large size and mass of the accelerated item, which has provides a better control of the impact speed and impact orientation.

The design specification (established by the authors) requires that both test rigs be capable of producing impact speeds between 15 ms^{-1} and 100 ms^{-1}. The upper speed is representative of the maximum speed seen by commercial aircraft during take-off and the initial climb out through 500 ft (i.e. the part of the flight profile where there is the greatest threat of insect contamination).

3.2 Stationary coupon impact test (SPIrIT)

The design of the SPIrIT rig is based on the principle of an air gun or air cannon (Fig. 1). Compressed air is used to accelerate the insect, which sits in a sabot (or cartridge). The system consists of a compressed air tank, which can be pressurised to 520 kPa. The firing mechanism incorporates a solenoid-operated diaphragm valve. The switch used to activate the solenoid can also be used to trigger a high speed camera.

The sabot, made of compressible foam, is accelerated down a smooth bore tube when the diaphragm valve is opened. The sabot has a multifunctional job. It provides a method to accelerate the insect(s) to high velocities, which is not possible by the introduction of the insect(s) into a high-speed air flow. The sabot also keeps the insects intact while undergoing the high initial acceleration. This has previously been reported as a problem when operating at high air velocities and pressures [17]. A light thread, attached to the sabot, stops the sabot from reaching the stationary test coupon, thus preventing any interaction with the impacted insect(s).

The test speed is provided by a chronograph (F-1 Shooting Chrony®), which measures the speed of the sabot. Images from a high speed camera (Photron® SA1.1) were used to calibrate the chronograph and to confirm that the insect impact speeds are representative of the chronograph-measured speeds. It was noted that the insect trajectory is variable, thus requiring a relatively large target area (which was selected to be 150 x 150 mm^2). For ease of post-processing, the target was divided into square sections of approximately 1 x 1 mm^2.

3.3 Accelerated coupon impact test (ASTIR)

A circular test coupon, with the material to be evaluated, is installed at the front of a custom-designed holder (Fig. 2). The concept for the ASTIR design (Fig. 3) is that it uses an air cannon to propel the coupon and its holder, which is retained within a tube at all times, to impact with the target insect (or insects).

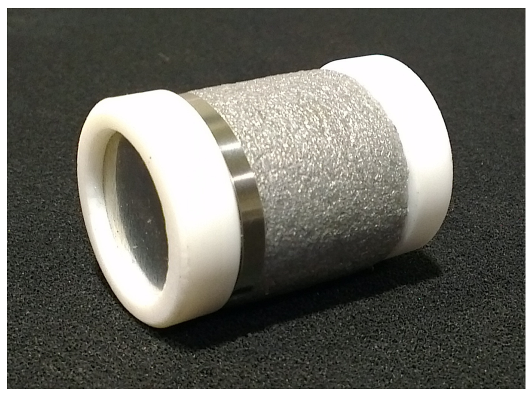

Fig. 2. Coupon holder for the ASTIR test rig

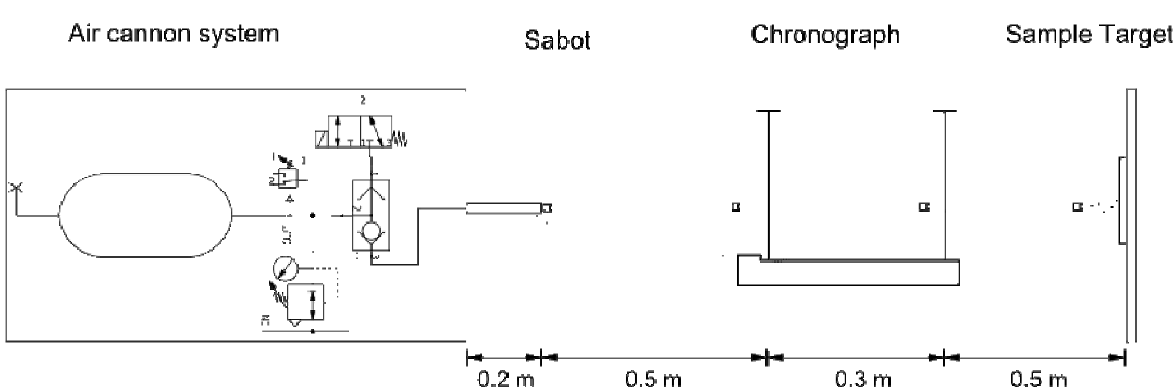

Fig. 1. Schematic of the SPIrIT test rig (not to scale)

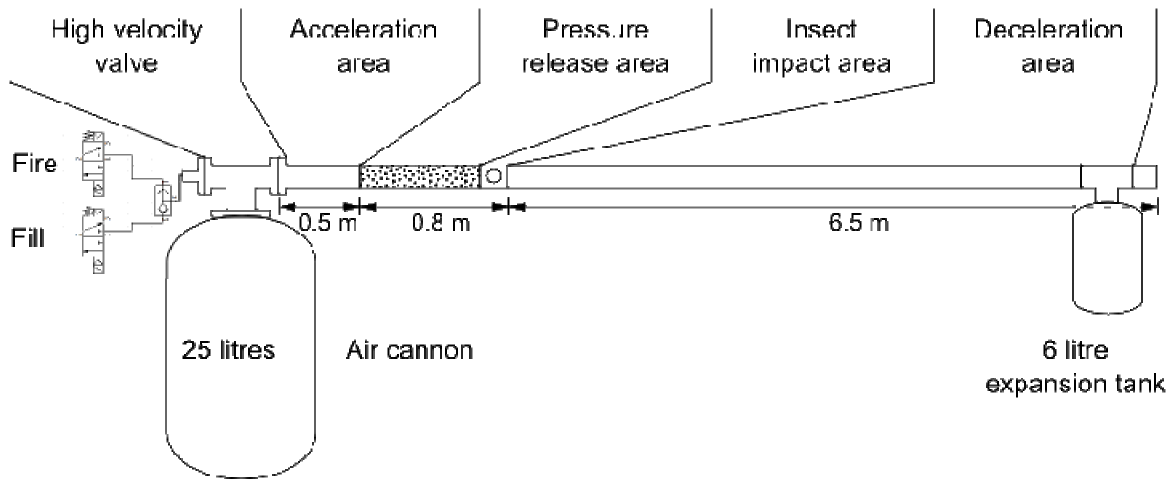

Fig. 3. Schematic of the ASTIR test rig (not to scale)

The coupon and holder assembly, which weighs approximately 40 g, is accelerated over a distance of 0.5 m, after which it is passes through a perforated area to release the excess pressure. The coupon then impacts the insect(s) and then passes into a sealed section of the tube where back pressure, built up by the movement of the coupon holder, decelerates it over a distance of 6.5 m.

The air cannon is operated by a control system, which improves the reproducibility of the firing pressure and, consequently, the impact speeds. The control system monitors the air cannon reservoir pressure, controlling the pressure to a set value through an electrical solenoid valve on the air pressure inlet. It allows for automatic firing when the set point is reached, or for a manual firing, through a second solenoid system. A chronograph is used to measure the speed of the coupon before it impacts with the insect(s).

4 Experimental methods

4.1 Materials

A number of low surface energy coatings have been evaluated in this study. The results of five selected coatings are herein reported: (1) Nusil™, which is a hydrophobic silicone plastic material; (2) a UV curable formulation containing an aliphatic urethane acrylate; (3) a polyurethane (PU) clear-coat, representative of that which is used on commercial aircraft; (4) a high cross-linked silane (HCS) sol-gel coating; and (5) a polyurethane (PU) silane sol-gel coating. In this study, the PU clear-coat (number 3, above) was used as a baseline or reference for comparison. All coatings were applied to 2024-T3 clad aluminium alloy.

Drosophila Melanogaster (fruit fly), cultured by the Life Sciences Department, University of Limerick, were used as the test insect. Drosophila Melanogaster was selected as it is most representative of a large proportion of surface deposits obtained by aircraft in flight conditions [18-20]. Drosophila has an average mass of 0.87 mg and is typically 0.67 mm long [1].

4.2 Preparation of test coupons

The surfaces were degreased with Methyl Ethyl Ketone (MEK) and allowed to evaporate to dry.

4.3 Contact angles measurements

Static contact angles were measured using a digital optical contact angle meter (CAM 200, KSV Instruments Ltd.), with polar and non-polar test liquids. Surface parameters of the test liquids, that is, deionized water and diiodomethane (ReagentPlus® 99% from Sigma Aldrich) are shown in Table 1. A 6 µL sessile drop was formed by depositing the liquid, using an auto-pipette, onto the substrate surfaces.

Both the left and right contact angles and drop dimension parameters were automatically determined from digitalized images. An average of at least 10 measurements at different positions on the sample was obtained five seconds after the drop was deposited to avoid evaporation or absorption errors. The room temperature was 18 ± 2°C. Guidelines given by European standard EN 828 were followed.

Table 1. Surface parameters of test liquids (mJ/m^2) [21, 22]

Test liquid	γ_s^p	γ_s^d	γ_s
Water	21.8	51	72.8
Diiodomethane	0	50.8	50.8

4.4 Surface roughness

Surface roughness (Ra) was measured. The tester (Hommel Tester T500) had a stylus tip of 5 µm (ISO 4287/1 and DIN 4768 standards were followed). Three measurements were taken for each coating type and an average calculated.

4.5 Insect impact test procedure

Insects were temporarily immobilized using CO_2 before inserting them into the sabot. Insect impact tests were conducted with the SPIrIT test equipment (described in Section 3.2) at approximately normal impact angles. The impact speed was varied between 60 m/s and 80 m/s.

A high speed camera (Photron® SA1.1) was used to measure the impact velocities and to calibrate the chronograph. Images of the impact event were studied to better understand the factors that influence the rupture of the insect exoskeleton. After impact, the airflow from the air cannon was maintained in order to simulate the effect of air blowing over the adhered insect during flight.

4.6 Area and height analysis

The residue area and height of the adhered insect matter on the test coupons was investigated and the results used to rank the candidate coatings. The insect residue area was determined using the analysis software ImageJ from images taken of the test coupons (using a Fujifilm FinePix S8000FD camera and a macroscopic lens). The height of insect residue were measured using a Baty® R400XL shadowgraph projector with a Metronics® Quadra Check 2000 monitor (accuracy to 0.001m). Area and height results (based on a minimum of five measurements per coating type) are given in Sections 5.3 and 5.4 respectively.

4.7 Topography

The topography of the insect residue on the test coupons were examined using a JEOL JCM 5700 Scanning Electron Microscopy (SEM), with magnifications ranging from x10 to x1000. The specimens were prepared with a conductive coating prior to imaging. Using Argon gas, the specimens were sputter coated with gold in a vacuum chamber. The specimens were mounted on an aluminium stub for analysis.

5 Results and discussion

5.1 Surface energy measurements

The surface energy (γ_s) of the coatings were obtained from contact angle data and their polar (γ_s^p) and dispersive (γ_s^d) contributions were calculated using the Owens-Wendt method. Coatings are arranged from lowest to highest surface energy values (Table 2).

Table 2. Measured surface energies (mJ/m^2)

Coating	γ_s^p	γ_s^d	γ_s
Nusil™	9.22	1.35	10.57
Urethane acrylate	19.29	3.01	22.30
Baseline	35.69	1.49	37.18
HCS	35.58	6.43	42.02
PU Silane	39.78	6.18	45.97

5.2 Surface roughness measurements

The arithmetic mean surface roughness (Ra) values, which were obtained for the five coatings, are recorded in Table 3 (arranged from lowest to highest roughness).

Table 3. Measured roughness values

Specimen	*Ra (µm)*
Baseline	0.02
Urethane acrylate	0.07
HCS	0.13
PU Silane	0.20
Nusil™	0.56

5.3 Area analysis

An analysis of insect residue area was conducted. It is postulated that the smaller the area of the rupture pattern, the less spreading of the haemolymph would occur and therefore less binding of the exoskeleton to the surface. The air flow over the aircraft surface would thus more easily remove insect debris, thereby reducing the amount of insect residue that remained adhered to the skin.

When comparing the residue areas (given in Fig. 4) to the surface energies (Table 2) and roughness values (Table 3), it is evident that there is simple correlation between these measures.

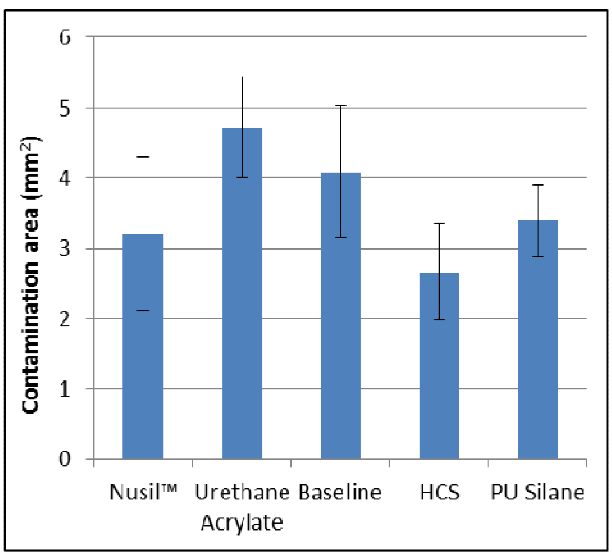

Fig. 4. Area measurements of insect residue

The HCS coating (high cross-linked silane) had the smallest residue area, but a relatively high surface energy of 42.02 mJ/m^2. The plastic silicone coating, Nusil™, was observed to prevent severe fracture of the exoskeleton and therefore only a small amount of haemolymph and other bodily fluids were released (Fig. 5). Consequently, only a small area of insect residue remaining on the surface after the insect had been blown off. This coating had the lowest surface energy (10.57 mJ/m^2), but the roughest surface of all coatings evaluated (Table 3).

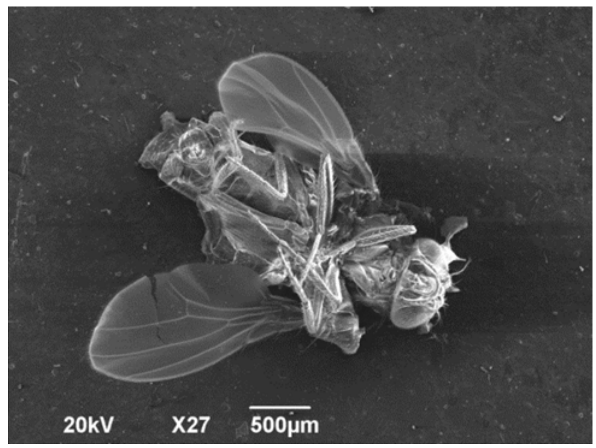

Fig. 5. SEM image of impacted Drosophila on Nusil™

5.4 Height analysis

Analysis of the height of the insect residue is important as the allowable height of a discrete particle for future LFC aircraft can be as low as 0.1–0.15 mm before it will induce boundary layer transition [2, 23–24]. The insect residue height measurements on all the coatings that were examined greatly exceeded these limits: the measured values ranged from 1.14 mm to 1.67 mm (see Fig. 6). The Nusil™ coating showed the lowest value of 1.14 mm, and the baseline polyurethane coating had the highest value.

It is evident that no direct correlation exists between the resulting residue area and the height. It might be expected (assuming that the residue volume is constant) that the coating with the smallest area would correspond to the greatest height, but this was not the case. It can be seen that the coating with the greatest residue height, i.e. the baseline polyurethane coating, had the second largest residue area. However, the Nusil™ coating, which had lowest height value, had the second smallest area. And, as noted earlier, it also had the roughest surface.

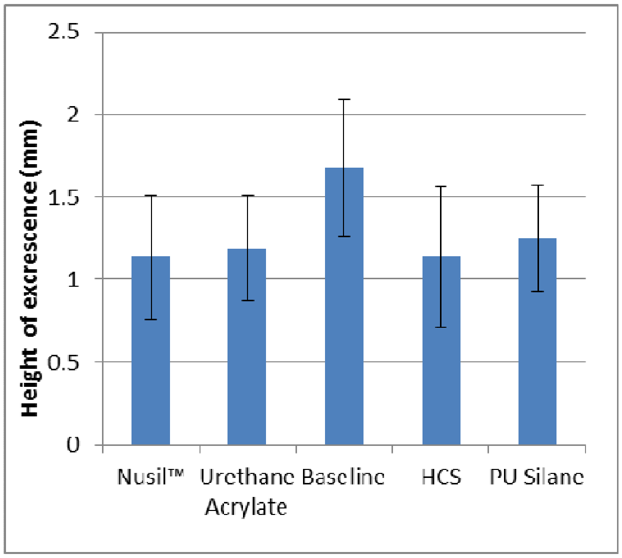

Fig. 6. Height measurements of insect residue

5.5 Surface roughness

During testing it noted that surface roughness has an influence on the spreading mechanism of the haemolymph upon impact. Experimentalists have hypothesized that a rougher surface may cause the formation of air pockets upon impact with the insect, which does not allow total adhesion and would result in easier removal of the debris, while others have found no correlation between surface roughness and insect residue adhesion [5, 20].

The results of the current study, in this respect, are inconclusive. In order to investigate the possible relationship between insect residue adhesion and surface roughness more extensive topography studies utilizing Scanning Electron Microscopy and confocal microscopy are necessary. A larger range of roughness values will be required to get a better understanding of the spreading mechanism of the haemolymph and how it relates to surface roughness.

5.6 Factors affecting rupture of an insect

The speed needed to fracture the insect's exoskeleton resulting in it releasing haemolymph and sticking to the test coupons were seen to be in the range of 20 – 30 m/s. It was noted that these speeds are greater than those reported by Coleman [1] for Drosophila Melanogaster. Such direct comparisons between different test results, however, can be misleading. For example, in the current study, air from the air cannon was allowed to blow onto the test coupons after impact (to simulate the effect of air flowing over the aircraft). It is conceivable that the air flow could have removed insects that may have ruptured but not stuck to the surface or left any residue trace.

Furthermore, it was evident from the current study, that there are several factors related to the insect impact event that have a bearing on the speed that is needed to cause the insect body to rupture – these include the age, gender and mass of the insect, and the insect body orientation on impact. A factor that was not considered in the current study is whether or not the insect's diet (i.e. wild or laboratory fed) had an influence on its ability withstand a severe impact.

From the test observations, it was concluded that a dominant factor influencing the rupture speed is the orientation of the insect body relative to the surface on impact. If the insect impacts the surface wings first, the likelihood of rupture is significantly less than if it impacted with its body first. This is due to the fact that the exoskeleton is most dense in the area where the wings meet the body and therefore offers significant protection against rupture. This part of an insect contains resilin, an elastomeric protein [25]. Resilin has a low stiffness (Young's Modulus of 1 MPa) and is capable of absorbing the impact force applied as well as releasing the energy back afterwards [26]. The flexibility of the exoskeleton and resilin protein therefore absorb some of the impact energy, preventing or reducing the likelihood of rupture. This also reduces the amount of haemolymph expelled and leaves a significantly different rupture pattern than if the insect impacts with the lower body first. This observation partly explains why there is a large scatter of measured rupture speeds, even when testing is conducted with insects of the same type, age and size.

It was also observed that at high impact speeds (60–80 m/s) the orientation of the insect does not have an effect on the extent of the insect residue. The orientation of the insect only appears to have an effect on the residue pattern at lower speeds, near that of the threshold rupture speed. The impact speed, when the orientation of the insect no longer has an effect, was not ascertained in this study (more tests would be needed at intermediate speeds).

6 Conclusions

(1) Although the surface energy of the coating does appear to influence the amount of contamination (residue) that results from high-speed insect impact, other factors, such as the effects of surface chemistry and roughness, also appear to influence the residue patterns.
(2) The low-surface-energy silicone coating Nusil™ performed well – it had the lowest residue height and the second smallest residue area of the five coating tested. It displayed lower susceptibility to insect adhesion compared to the baseline polyurethane (PU) clear-coat (representative of that which is currently used on commercial aircraft).
(3) The measured height of the insect residue varied from 1.14 mm to 1.67 mm for the coatings tested (this exceeds typical excrescence height limits associated with a laminar-turbulent transition of the boundary layer).
(4) No direct correlation was found between the area and the height of insect residue after impact.
(5) The minimum speed needed to rupture the cuticle of Drosophila Melanogaster (releasing haemolymph such that the insect adhered to the test coupon) was observed to be in the range of 20 – 30 m/s. The rupture speed was seen to depend significantly on the orientation of the insect body relative to the test surface on impact.
(6) Surface roughness has an effect on the spreading mechanism of the haemolymph. More extensive topography studies on a larger sample population, however, are necessary to understand the relationship, if such exists, between insect adhesion and surface roughness.

Acknowledgements

This work is supported by the European Union through FP7 Framework project AEROMUCO (AEROdynamic surfaces by advanced MUlti-functional COatings). The authors would like to acknowledge the following organisations for providing test materials and data for this study: CREST, Dublin Institute of Technology, Dublin, Ireland; EADS IW, Ottobrunn, Germany; Photon et Polymers (PnP), Lutterbach, France; and Dassault Aviation SA, Paris, France.

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