

A new test apparatus to measure the adhesive shear strength of impact ice on titanium 6Al-4V alloy

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Abstract

We present a new shear test which may be used in an icing environment. Ice is formed on a jig containing the sample material and this is then loaded by a forcing mechanism to effect the adhesive test. It allows impact (atmospheric) ice adhesive shear tests to be undertaken without disturbance or delay, in icing conditions. Finite element analysis is used in order to evaluate the controlling shear stresses in the most highly stressed zone of the ice/substrate interface and some sample experimental data is given for the adhesion of some impact ices to Ti-6Al-4V alloy with different surface finishes. The adhesion forces reported, represent peak values rather than spatially averaged stress values. Therefore values of adhesive shear strength obtained are higher than previous authors (in the range from 2 to 14 MPa instead of 0.05 to 0.5 MPa).

Keywords: atmospheric ice, impact ice, finite element analysis, shear strength, fracture mechanics

1. Introduction

Impact ice (also known as atmospheric ice) is the term for ice formed from supercooled water droplets impinging on a solid body. Such droplets can exist extensively in clouds as nuclei which are able to cause the condensation of a droplet, are often not effective as freezing nuclei until the temperature

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6 falls to several tens of degrees below freezing point [1]. The super-cooled
7 water droplets will however freeze readily on ice particles (producing hail for
8 instance), aircraft, ships, power transmission lines, trees, wind turbines and
9 many other natural and man-made objects leading to a range of hazards.
10 This study has been conducted for the particular case of ice shedding from
11 aeroengine fan blades. In aircraft engines, fans are not actively protected
12 with any anti-icing or deicing system. Hence, when ice builds up on fan
13 blades, it generally sheds due to the centrifugal force acting on it. Ice pieces
14 can damage the nacelle or be ingested by the engine and damage components
15 further down stream. Therefore it is of the highest importance to determine
16 the strength of ice adhesion to the blade in order to allow the ice fragment size
17 to be determined. Furthermore, in the view of the potential to reduce cost
18 of testing, manufacturers are trying to model ice shedding from engine parts
19 and need values for the adhesive strength (in shear and tension) together
20 with the cohesive strength of ice.
21 Adhesive shear strength has been extensively studied during the last century,
22 however only few authors have reported data on adhesive shear strength
23 of impact ice. Impact ice is quite difficult to obtain. It is necessary to
24 have either a natural site, a cold room or icing tunnel where water can be
25 sprayed. The second difficulty is to have a test apparatus able to work in
26 these conditions. The new test apparatus developed at Cranfield university
27 is able to measure the adhesive shear strength of ice attached to a substrate
28 in a running icing tunnel. Given that the thermal expansion coefficient of ice
29 is generally reported to be approximately 50 microstrains per degree at -10°C
30 (six times that of Titanium) and that significant creep is to be expected at
31 these high homologous temperatures, the means to perform a shear test on
32 ice which is still forming is expected to be of value.

33 **2. Previous studies**

34 Two types of shear test have been described for impact ice: “static” tests
35 where the ice is pushed, pulled or twisted to separate it from the body it has
36 grown on, and rotational tests where the ice is removed due to the centrifu-
37 gal force. These different types of test used lead to a wide range of values
38 reported for the adhesive shear strength (figure 1).

39 Most of the results fall in the range between 50 and 500 kPa. All authors
40 presented a range of values due to the fact that ice is a brittle material which
41 means that scatter will be involved in the results and that several tests need

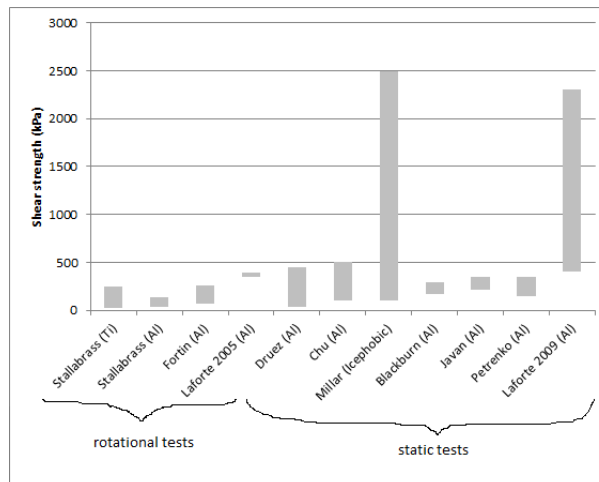


Figure 1: Range of adhesive shear strength values found by the different authors

42 to be carried out for each icing condition or substrate coating tested. Statis-
 43 tical analysis have been conducted on the experimental results and a mean
 44 value and standard deviation have usually been reported. However the scat-
 45 ter does not by itself explain the difference of value reported by the different
 46 authors. Three major points could explain the difference in the results: the
 47 method of measurements, the different conditions used to form the ice and
 48 the properties and the state of the substrate surface.

49 The first rotational test was carried out by Stallabrass and Price [2]. A cylin-
 50 drical specimen was mounted on a helicopter rotor blade. Ice was formed by
 51 spraying water in a cold room. The blades were rotating at a constant speed
 52 of 500 RPM. The centrifugal load was determined using strain gauge mea-
 53 surements. As ice built up, the centrifugal load increased until the adhesive
 54 or cohesive strength of ice was reached and ice shed. Five different materials
 55 were tested (aluminium, stainless steel, titanium, teflon and viton) through
 56 a range of temperature between -7°C and -18°C . No special care was taken
 57 to clean the blades as it was considered that in application, blades were
 58 not cleaned in any way and were contaminated by dust and other sorts of
 59 particles. The adhesive shear strength of aluminium and titanium were re-
 60 spectively found to be in the range from 30 to 130 kPa and from 20 to 250
 61 kPa. Whilst this method is realistic for application to spinning components
 62 in using centrifugal force to apply the load, it does not force the fracture to
 63 follow the interface between the ice and the substrate. Furthermore, it is not

64 always possible to see whether the fracture event was confined to the inter-
65 face (adhesive) or whether the ice broke within itself (cohesive). The authors
66 reported significant cohesive ice fracture with viton and reported that it was
67 difficult to determine the presence or absence of ice on the metal substrate
68 surface. Therefore, the results do not tell us with certainty what the ice bond
69 strength was.

70 Fortin and Perron [3] used a similar method but the ice was accreted directly
71 on the blades of a helicopter rotor. The rotating speed was kept constant
72 around 3230 RPM and, as the ice built up, the power needed to rotate the
73 blades increased. An ice shedding event was recorded as a sudden drop in
74 power. The blades were made of aluminium alloy and were resurfaced with
75 scotch brite after each test. Four temperatures spanning the range between
76 -5°C and -20°C have been tested. The adhesive strength is calculated from
77 the balance of the centrifugal, cohesive and adhesive force. The assumption
78 made was that the ice thickness has a linear increase from hub to tip. Values
79 between 70 and 260 kPa were found for the shear strength of ice on Alu-
80 minium. Like for the test rig used by Stallabrass and Price, this test rig does
81 not guarantee that an adhesive break can be made. The crack responsible
82 for the fracture will take the easiest path to propagate, either within the ice
83 or at the interface. In case of cohesive failure, the rotational test rigs will
84 then provide lower values for what is taken as the shear strength compared to
85 purely adhesive shear test rigs. In their paper, Stallabrass and Price specified
86 that their results at low temperature were probably underestimated by 50%
87 due to an overestimation of the area of contact in case of cohesive failure.

88 Laforte and Beisswenger [4] used a slightly different system. Icing was built
89 up at the extremity of beams by spraying water and the beams were then
90 placed in a centrifuge. The speed of the centrifuge was increased from 0,
91 at a rate of 300 RPM/s, until ice shedding occurred. The shedding event
92 was picked up by two piezoelectric cells which can detect vibrations, placed
93 on the side of the centrifuge casing. The shear strength was calculated by
94 dividing the centrifugal force by the iced area. An average value of 350 kPa
95 was obtained for ice on aluminium at a temperature of -10°C . Nothing was
96 said about the cleanliness or the roughness of the beams. In this test, only
97 the values when adhesive fracture occurs were kept. The authors specified
98 that cohesive fracture can happen but the tests were discarded.

99 In general, the rotational tests give lower values than “static” (non-rotating)
100 test rigs. This is probably due to the fact that rotational test rigs are subject
101 to additional forces like vibrations, aerodynamic forces or local heating which

102 are not taken into consideration in “static” test rigs. These additional forces
103 are thought to contribute to crack initiation and propagation and therefore
104 results in lower apparent force needed to debond the ice. Whilst rotational
105 tests are probably the best method to test how ice sticks to rotating compo-
106 nents, they cannot give a suitable value for pure adhesive shear strength.
107 Both Druetz et al. [5, 6] and Chu and Scavuzzo [7–9] used a test apparatus
108 which pushed the ice accreted around a metallic cylinder. In both cases the
109 ice was formed in an icing tunnel by spraying water on the cold metal sur-
110 face, then the mechanical test was carried out. In their experiments, Druetz
111 et al. used a metal disc to push the ice until it was removed from the sur-
112 face and the force was recorded by four strain gauges. The shear strength
113 was calculated by dividing the force applied by the contact area between the
114 ice and the substrate. Each adhesion measurement was made at the same
115 temperature as the icing formation but a delay of 20 minutes was observed
116 before any measurement. Substrates were carefully cleaned and dried be-
117 fore ice accretion. Values in the range from 40 to 450 kPa were obtained on
118 aluminium. Substrate of different roughness have been tested and adhesive
119 shear strength has been found to increase with increasing roughness until it
120 reaches a plateau for a roughness of $20 \mu\text{m}$. Chu and Scavuzzo’s specimens
121 were made using two concentric cylinders. A window on the outer cylinder
122 allowed ice to stick on the inner cylinder which is made of the metal of in-
123 terest. The adhesive shear force was measured by pushing the inner cylinder
124 until ice became detached. A load cell was used to record the force and a
125 linear variable displacement transducer to determine the instant of shedding.
126 The test temperature was obtained by heating the interface ice/substrate
127 using a heating element placed at the center of the inner cylinder. The inner
128 cylinder was dipped in acetone and allow to dry. All parts were assembled
129 using tongs to minimise contamination by hand oil. Different material rough-
130 ness have been tested and this parameter has been found to influence largely
131 the adhesion of ice. Values between 100 and 500 kPa have been obtained
132 depending on the icing conditions. In all these tests, only purely adhesive
133 shear strength values were reported. The authors reported some cohesive
134 failure especially with rime ice but the values were discarded. In these tests
135 the ice is allowed to rest after being built up, so any thermal stresses that
136 could arise as a results of the solidification process will not be involved in
137 the mechanical test. Chu and Scavuzzo even used a different temperature
138 for growing and testing the ice. As the thermal coefficient of expansion of
139 ice is relatively high compared to the thermal coefficient of metal and as the

140 ice formation process involves some cooling, a small variation in temperature
141 will induce high thermal stresses which would modify the ice adhesion prop-
142 erties and might lead to a bias of the adhesive shear strength.

143 Millar [10] has studied the adhesion of ice on a wing. After accretion, a
144 piece of ice is isolated by removing the neighboring ice and then it is pushed
145 using a hydraulic ram device. Values between 100 and 2500 kPa were ob-
146 tained depending on the material tested (range of icephobic materials like
147 polyurethane, teflon paint or silicone).

148 The adhesive strength can also be obtained by bending a beam of mate-
149 rial which ice is accreted on. Blackburn et al. [11] have argued that, for a
150 specific thickness of ice, when the neutral axis is positioned at the interface
151 ice/substrate, the ice is debonded adhesively and therefore the adhesive shear
152 strength can be obtained. This test was conducted in two steps: the first
153 one where the ice was accreted on aluminium beams in a cold chamber at
154 -10°C and the second one where the iced beams were tested. Several test
155 have been conducted and an average value of 230 kPa has been obtained.
156 No information on LWC, tunnel wind speed or droplet size have been given
157 hence a direct comparison with other values is not possible. Again the ice
158 was fractured in conditions which were not the same as those under which
159 it formed (different static temperature and the ice was allowed to rest after
160 accretion).

161 Javan-Mashmool et al. [12] also tried to use the bending properties of an
162 aluminium bar to measure the shear strength of ice bonded to it. Prior to
163 the ice accretion, piezoelectric film sensors were attached to the aluminium
164 beams. The iced aluminium beams were clamped onto an electric shaker and
165 the ice adhesion was measured by monitoring bending vibrations. The test
166 temperature was set at -10°C and the wind speed at $3.3\text{ m}\cdot\text{s}^{-1}$. An average
167 value of 285 kPa was obtained.

168 Laforte and Laforte [13] reported about other tests to measure the adhesion
169 of ice on an aluminium substrate. They used tests where the ice was only
170 constrained at the interface ice/substrate and the force was applied to the
171 substrate and not to the ice. Due to the applied force, the substrate was
172 strained and the strain propagated into the ice. The force was applied in
173 three different ways: tension, torsion and bending. In all tests, the adhesion
174 of ice was measured in terms of deicing strain directly measured by strain
175 gauges placed on the aluminium bar. Normal stress or shear stress at the
176 instant of shedding can then be calculated from the strain value and the
177 Young's modulus. Only the torsion test gave a value for pure shear strength.

178 Average values of 2300, 1000 and 400 kPa were obtained for ice thickness of
179 2, 5 and 10 mm respectively. With a thicker sample of ice, the probability of
180 larger defects in the ice increases which results in a lower value of the ice ad-
181 hesive shear strength. Furthermore, two different materials, aluminium and
182 nylon, have been tested with different surface finishes and results showed an
183 absence of influence of the substrate material but an increase in the shear
184 strength with roughness. Here again time was allowed between ice formation
185 and mechanical test for relaxing the internal stresses.
186 These tests [5–13] were carried out in two steps: ice was made in one location
187 then moved and was tested in another location. Moving the ice introduce
188 mechanical and thermal shocks that could influence the values obtained [14].
189 The only static experiment carried out in a running icing tunnel was done
190 by Petrenko [15]. Stainless steel wires of 0.5 mm in diameter were placed
191 on a surface and, as ice accumulated, the wires were pulled out. The force
192 needed to pull the wires was measured using a force sensor. The time at
193 which the wire was pulled and the tensile force were recorded. The adhesive
194 shear strength of ice was obtained from the measured tensile force and the
195 iced surface of the wires. A curve of adhesive strength variation through time
196 was obtained. For ice made at a temperature of -10°C and a tunnel speed
197 of $20 \text{ m}\cdot\text{s}^{-1}$, values between 150 and 350 kPa were obtained depending on
198 the LWC of the cloud. The thickness of the wires were chosen in such a way
199 that the wires could not stretch as they were pulled out of the ice.

200 **3. The new ice shear test**

201 The main objective of this new test is to provide an adhesive shear test
202 which is able to be conducted in a working icing tunnel and provide a shear
203 strength value.

204 The ice was grown over the face of a plunger and the substrate (figure 2).
205 The substrate has a surface parallel to the direction in which the plunger
206 can be made to move. Once an ice layer of sufficient thickness to provide
207 a satisfactory stress distribution for the test has been accreted, the plunger
208 was pushed with increasing force until the ice becomes detached from the
209 substrate by the shearing action. The pressure needed to move the ice was
210 measured and then converted to a shear strength value through a finite ele-
211 ment analysis.

212 Several test devices could be placed in the tunnel at the same time. Each
213 test device included a substrate, a plunger, a rubber tube and a supporting

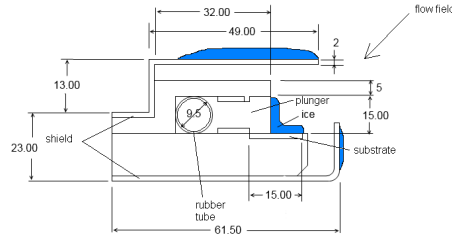


Figure 2: Schematic diagram of the shear test

214 structure. The substrate can be changed easily so different materials can be
 215 tested. Nitrogen gas under pressure passed into the rubber tube which, by
 216 inflating, pushed the plunger. The rate at which the gas was allowed into
 217 the rubber tube can be varied resulting in controlling the strain rate.
 218 The test rig was placed in the tunnel at an angle of 45° with respect to the
 219 flow stream. In this way both the substrate surface and the plunger wall
 220 were uniformly covered by ice. Ice growth on top and bottom parts of the
 221 test rig were mainly avoided by the presence of two shields which caught the
 222 supercooled water droplets before they impinged on surfaces. This prevented
 ice from bridging between the moving and the fixed parts. For the same



Figure 3: Test rig

223
 224 reason, the front face of the plunger extended for the full width of the test
 225 fixture so that the ice connecting the plunger to the substrate was isolated
 226 from other ice on the test fixture (figure 3).
 227 The rubber tube was connected to a source of high pressure nitrogen through

228 a pressurization system. The pressurization system consisted of a system of
229 valves allowing several test fixture to be operated independently. A needle
230 valve was employed to select the flow rate of the gas and an electronic valve
231 was used to allow gas to enter the system. A house-made connector consisting
232 of two wires, one positioned on the top of the device and the other between
233 the plunger and the overall structure, was used to determine the instant when
234 the plunger starts to move. The two wires were connected through a little
235 electrical circuit made up of resistors, battery and lights. During the setting
236 of the test, the plunger was pulled back against the structure so the circuit
237 was closed and a current could be measured. The lights were used as a visual
238 indication of the circuit being close or open. When the plunger started to
239 move, the electrical circuit became open, the light went off and a drop in
240 the voltage of the circuit can be observed (figure 4). In most of the cases,
241 the drop of voltage corresponded to a change in the slope of the curve representing the pressure increase through the rubber tube. After the movement

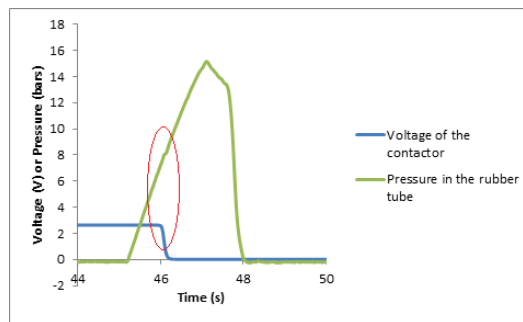


Figure 4: Graph representing the pressure of the gas going through the rubber tube (green curve) and the voltage of the current going through the contactor (blue curve) during a mechanical test

242
243 of the plunger (and therefore detachment of ice), the pressure was still able
244 to increase as there was no escape route for the gas. The whole pressuriza-
245 tion system had to be purged by the operator manually. The pressure was
246 measured using a pressure transducer and a recording of one value each ms
247 was made by a data acquisition system (DI-718B from DATAQ instruments).
248 The test rigs were placed in the tunnel on two support bars. Attention was
249 made to constrain the rubber tubes well so they can only expand inside the
250 test rig and not on the outside (which can lead to a bursting of the rub-
251 ber tube). Natural rubber tubing was used because of its exceptional strain
252 capability at the temperature required.

253 4. Test procedure and analysis

254 The substrate surfaces were first cleaned with ethanol and dried using a
255 hot air gun. Special care was made to remove any water which might have
256 gone under the plunger. The test jigs were covered and the air supply to the
257 tunnel atomising system was switched on so that any water still in the nozzles
258 can be purged without it landing on the test jigs before the experiment was
259 started. The test jigs were then uncovered, the tunnel working section was
260 closed and the main fan and the cooling system were started. The different
261 parameters (LWC, temperature, tunnel speed) were set and when the tunnel
262 was in stable condition, the water was sprayed.

263 A thickness of 3 mm was found to be best to obtain a clean adhesive re-
264 moval of the ice from the substrate in a single piece. Therefore when such
265 a thickness was reached, which took about 5 minutes, the mechanical test
266 could be started. The tunnel was kept running with the water still being
267 sprayed. Each test device was operated in turn by selecting the individual
268 valve and switching on the electrical valve until the ice sheded. The substrate
269 was visually free of any ice. Therefore the ice fracture mode was assumed to
270 be purely adhesive.

271 The force applied by the plunger to the ice was calculated from the pressure
272 measured by the pressure transducer taking into account the thickness of
273 the rubber tube walls. The rate at which the test fixture is pressurized was
274 controlled to approximately 10 bars per second for the current investigation.
275 This typically gives fracture in one to two seconds. The strain rate is of the
276 order of 10^{-4} s^{-1} .

277 A post-processing task consisted of recovering the instant of shedding and
278 noting the value of pressure needed to shed the ice. This latter was called
279 critical pressure measured ($P_{c \text{ measured}}$). It has to be drawn to the attention
280 of the reader that the value of $P_{c \text{ measured}}$ represent the pressure of the gas
281 needed to move the plunger. Hence, to calculate the critical pressure applied
282 on the ice (P_c), the thickness of the rubber tube and the force required to
283 push the plunger when no ice is present need to be taken into consideration.
284 The former point is a coefficient obtained from the geometry of the rubber
285 tube and directly applied to the measured critical pressure value. The lat-
286 est required an experimental test in a dry icing tunnel at a temperature of
287 -10°C . The pressure required to move the plunger was measured at 1.08 bars
288 ($P_{c \text{ measured no ice}}$). This value was used as an offset of the critical pressure

289 measured during the test (equation 1).

$$P_c = P_{c\text{ measured}} \times \frac{d_0 - 2e}{d_0} - P_{c\text{ measured no ice}} \quad (1)$$

290 where d_0 is the diameter and e the thickness of the rubber tube.

291 As ice is usually considered as a brittle material, the experimental results
292 will include some scatter, even when a lot of care is taken to reproduce
293 the same conditions exactly . To deal with this, several values of critical
294 pressure were obtained for each condition. It has been proved previously that
295 the strength of brittle materials follows a Weibull distribution [16], hence, a
296 statistical analysis was run. The software Statistica ¹ was used and, for each
297 conditions, the software determined the Weibull distribution that best fitted
298 the data (two parameters Weibull distribution). These parameters consist
299 on the shape parameter (or Weibull modulus) which give an indication of the
300 distribution of the flaws in the material, and on the scale parameter which
301 represents the spread of the distribution. A low value of the shape parameter
302 means that the flaws are distributed non-uniformly and that the strength
303 will present more scatter, whereas a high value means a higher reliability
304 in the strength value. The Weibull modulus ranged mainly between 4 and
305 8 (as a comparison, Weibull modulus for ceramics are in the range from 5
306 to 20 and about 100 for steel). In a two parameters Weibull distribution
307 the scale parameter is the value at which 63% of the specimens would have
308 failed. At the end of the process a mean value and a standard deviation were
309 calculated using equations 2 and 3 where λ is the scale parameter, k is the
310 Weibull modulus and Γ is the Gamma function.

$$\bar{m} = \lambda \times \Gamma(1 + 1/k) \quad (2)$$

$$\sigma = \sqrt{\lambda^2[\Gamma(1 + 2/k) - (\Gamma(1 + 1/k))^2]} \quad (3)$$

311 5. Determination of shear strength

312 Two different approaches were used to calculate a shear strength value
313 from the critical pressure:

- 314 - A shear strength value which is an average over the whole area of ice
315 in contact with the substrate.

¹Statistica is a statistics and analytics software developed by StatSoft, <http://www.statsoft.com>

316 - A shear strength value which is a peak value related to the most highly
317 stressed region where the plunger, the substrate and the ice meet.

318 The first value is useful to compare with values reported by other authors
319 while the second is desirable for general modelling efforts away from experi-
320 ments.

321 The average value, τ_{av} , was calculated from the classic definition of shear
322 stress, $\tau = F/A$, where τ is the shear stress, F is the force applied and A is
323 the area of contact. Here F is the pressure acting on the plunger surface and
324 is equal to $F = P_c \times r_0 \times w$ where P_c is the critical pressure needed to move
325 the plunger and therefore detach the ice, r_0 is the internal diameter of the
326 rubber tube (0.9 cm) and w is the width of the jig. The area of contact, A,
327 represent the area of substrate in contact with the ice and is equal to 1 cm
328 times the width of the jig. Hence the average shear strength was obtained
329 from

$$\tau_{av} = 0.9 \times P_c \quad (4)$$

330 The average shear stress does not reflect the true stress state at the ice/substrate
331 interface which is affected by edge effects. In particular, even though the ap-
332 plied pressure is constant, the stress distribution at the interface will be
333 non-uniform; its near field will decay with $r^{-1/2}$ away from the edge (where
334 the plunger apply the force on ice) of the interface [17, 18]. Thus, the average
335 shear strength τ_{av} will act as a scalable measure of the applied pressure at
336 which the sliding begins. The adhesive shear strength, on the other hand,
337 may only be determined from further considerations regarding the form of
338 the interfacial stress distribution.

339 The peak shear strength was obtained from Finite Element Modelling. The
340 commercial software Abaqus 9.2 ² has been used for the determination of a
341 correlation between the critical pressure and the stress intensity at the junc-
342 tion between the ice, the interface and the plunger. The local shear strength
343 was then calculated from the latter using the average grain size as a typical
344 flaw size. The use of a finite element analysis allowed us to get the value of
345 the adhesive shear strength through the fracture toughness at the location
346 the force was applied. Therefore, the value obtained will not be an average
347 value along the substrate surface but the exact value of shear stress needed

²Abaqus is the name of a finite element analysis software developed by Simulia, <http://www.simulia.com>

348 to detach the ice at the point where the fracture initiates.
 349 The finite element model, the geometry of which is shown in figure 5, con-
 350 sisted of a rectangular shaped piece representing the substrate, a “L” shaped
 351 piece representing the ice and another piece representing the plunger which
 have a circular wall at the location where the pressure was applied. The

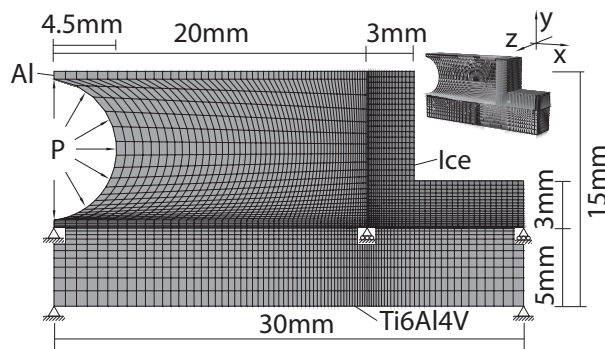


Figure 5: Schematic of the Finite Element Model

352
 353 plunger and the ice were tied together using a tied constraint, hence these
 354 two parts will stay stuck together throughout the whole simulation. The
 355 plunger and the substrate were linked with a surface to surface contact inter-
 356 action with no friction so the plunger was allowed to slide on the substrate
 357 surface. The ice and the substrate were linked by a tied constraint. This
 358 simulation was made to calculate the shear strength of ice corresponding to
 359 the pressure needed to remove the ice. The ice was not supposed to be re-
 360 moved until this pressure was reached, then the ice can be assumed to be
 361 completely tied to the substrate for the whole simulation.

362 During the mechanical test, the gas pressure inflates the rubber tube which
 363 will apply pressure to the plunger. To simplify the model, the rubber tube
 364 was not represented as a part and the gas pressure was applied directly on the
 365 plunger curved wall with an allowance made for the thickness of the rubber
 366 tube. The pressure was assumed to be uniform and had a set magnitude. It
 367 was applied with a smooth amplitude step to ensure a quasi-static simula-
 368 tion. Two boundary conditions were set: one to restrict the substrate from
 369 any movement (encastre boundary condition on the bottom surface of the
 370 substrate) and the other to restrict the plunger movements to only transla-
 371 tion in the horizontal direction x.

372 The mesh has been particularly refined at the corner of the “L” shaped ice

373 piece as this is the location of the crack initiation. An 8 nodes linear brick el-
374 ement with reduced integration and hourglass control was used for the mesh
375 of all parts. A more detailed discussion on the mesh dependence can be
376 found in [19].

377 The finite element analysis was conducted in 3D. This was done to account
378 for potential edge effects around the free surfaces, which may have affected
379 the stress distribution along the ice/substrate interface. By gradually reduc-
380 ing the width of the system along the z direction, we verified that given high
381 translational symmetry of the system and its loading along this z direction,
382 the system works in plane strain.

383 Furthermore, the observed edge effects were minimal, so we were able to re-
384 duce the width without affecting the distribution of stress in the bodies and
385 along the interfaces.

386 The substrate material was titanium alloy, Ti6Al4V, with a Young's modu-
387 lus and density of 113 GPa and 4130 kg.m⁻³ respectively. Despite the fact
388 that the Young's modulus of ice could vary from 2.5 to 14 GPa and the ice
389 density from 700 to 914 kg.m⁻³ depending on the icing conditions, an hy-
390 pothesis was made that these two parameters were constant over the range of
391 icing conditions explored in the present investigation. A value of 870 kg.m⁻³
392 was chosen for the ice density which is an average value found through the
393 literature. For the Young's modulus of ice, a value of 13.2 GPa was cho-
394 sen which correspond to an average of the values measured during previous
395 experiments on a few icing conditions (obtained by measuring the speed of
396 sound through ice [19]). These two values are dependent on the ambient
397 conditions used to build the ice. However, as a first approximation and in
398 lack of values, it was assumed that they would be constant throughout the
399 whole range of conditions tested. The plunger material was Aluminium alloy,
400 with a Young's modulus of 70 GPa and a density of 2700 kg.m⁻³.

401 As the pressure value increases, the shear stress build up. The stress field
402 will be near singular at the edge of interface (as shown by Bogy [20]) and
403 away from it decay with $\approx r^{-1/2}$ in the near field. A path reading for out
404 putting local stress components was set at the middle of the ice's interface.
405 The values of the shear stress along the path were taken. A value similar to
406 the stress intensity factor, K_{II}^* , associated with the interfacial shear stress
407 distribution was defined as

$$K_{II}^* = \tau\sqrt{2\pi r} \quad (5)$$

408 where τ is the shear stress and r is the distance from the edge.
 409 The value of the stress intensity factor K_{II}^* when the applied pressure reaches
 410 its critical value P_c is a universal measure of the interfacial adhesive strength.
 411 Barring natural experimental scattering, the critical stress intensity, K_{IIc}^* , is
 412 a characteristic of each material and is independent of geometry or loading. In
 413 order to determine the K_{IIc}^* value from the FEM analysis, the stress intensity
 414 factor was calculated from the stress distribution and plotted against the
 415 distance from the edge. The curve obtained was fitted by a polynomial
 416 equation. The value for $r = 0$, was the critical stress intensity K_{IIc}^* . A
 417 correlation can be obtained for different critical pressure applied (figure 6):

$$K_{IIc}^* = 182128 \times P_c \quad (6)$$

418 where the critical pressure, P_c , is expressed in MPa and the critical stress
 419 intensity factor, K_{IIc}^* in $Pa m^{1/2}$. As may be seen, a linear fit between K_{IIc}^*
 420 and P_c was obtained which is in agreement with theoretical expressions for the
 421 contact stress field between wedges and planar surfaces of dissimilar materials
 [18]. From the value of the critical stress intensity and taking the grain size

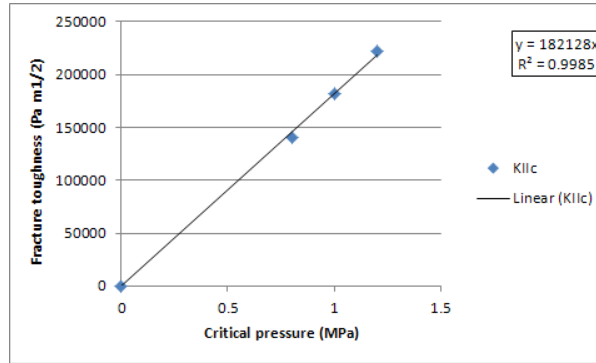


Figure 6: Correlation between critical pressure and fracture toughness

422 as an indication of material inherent defect size, a shear strength value can
 423 be calculated:
 424

$$\tau = \frac{K_{IIc}^*}{\sqrt{\pi a_g}} \quad (7)$$

425 where a_g is the average grain size in m.
 426 The use of a_g as the representative lengthscale with which to define the shear
 427 strength is justified on the grounds that, give that ice is brittle material, the

428 grain size is expected to control the initial crack size and the separation
429 between defects [21–24]. In the following results, the average grain size was
430 obtained from measurement using a nail varnish replica method [25].

431 6. Results

432 Each result presented was derived statistically from five or more shear
433 tests performed in the same condition. On the graphs, the crosses represent
434 the main value and the error bars represent one standard deviation above
435 and below the main value. Shear strength was obtained using the correlation
436 presented in the previous section and the average grain size measured during
437 microstructure observations. Assumptions have been made that the Young
438 modulus, the poisson ratio and the density of the ice do not vary significantly
439 with tunnel temperature, tunnel wind speed or LWC. The values used are
440 respectively 13.2 GPa, 0.31 and 870 kg.m⁻³. In all the following, the sub-
441 strate used was made of titanium alloy Ti-6Al-4V and had a mirror polished
442 finish.

443 6.1. Influence of temperature

444 The temperature referred to is the total temperature (that is the apparant
445 temperature of the flow once it has been brought to rest) inside the tunnel.
446 It was set prior to the ice accretion process and was kept constant during the
447 whole experiment. The runs made to investigate the influence of temperature
448 have been made using a low and a moderate value of the LWC (respectively
449 0.4 g.m⁻³ and 0.7 g.m⁻³). The tunnel wind speed and the droplet size were
450 kept constant at respectively 50 m.s⁻¹ and 20 μm for the whole series of ex-
451 periments.

452 The shear strength has been found to increase as the temperature decreases
453 in the range of temperature from -2°C to -12°C (figure 7 and 8).

454 The values obtained range between 2.1 and 10.8 MPa which is a lot higher
455 than the values found in the literature. At a temperature of -10°C, values
456 less than 500 kPa were usually reported by previous authors. In the present
457 study, the ice was shed from its substrate in exactly the same conditions
458 as during its formation; meaning that no redistribution of thermal stresses
459 has been involved within the ice. Also the shear force reported relates to
460 the peak shear force where fracture initiates, not the mean force/area factor
461 usually used. Shear stress decreases as the distance from the edge increases
462 meaning that an average value would be lower than the value at the edge.

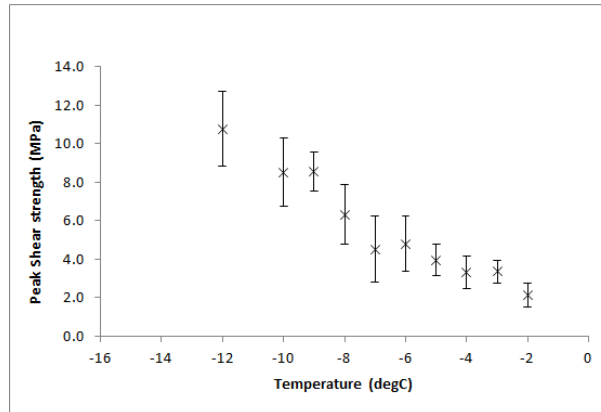


Figure 7: Effect of temperature on the peak shear strength of ice (LWC=0.4g.m⁻³)

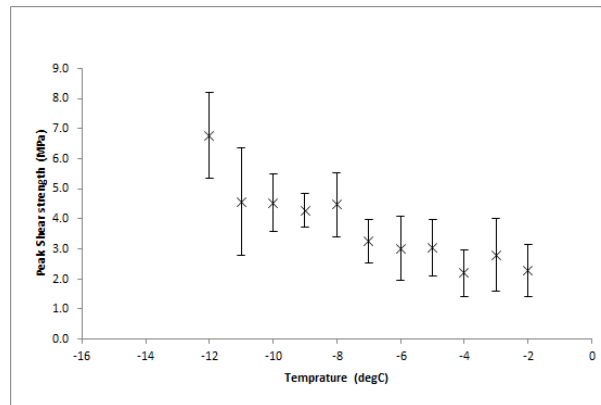


Figure 8: Effect of temperature on the peak shear strength of ice (LWC=0.7g.m⁻³)

463 By using equation 4, an average shear strength was calculated. The values
 464 obtained lie in the range between 0.3 and 1.0 MPa which is closer to the
 465 values obtained by previous authors.

466 The trend of adhesive shear strength to increase with decreasing temperature
 467 is relatively comparable with the previous studies. Druetz et al. [5, 6], Chu
 468 and Scavuzzo [7–9], Stallabrass and Price [2] and Fortin and Perron [3] re-
 469 ported an increase in shear strength as the temperature decreases with either
 470 a constant or a maximum value reached at a certain temperature.

471 *6.2. Influence of Liquid Water Content (LWC)*

472 A series of tests has been conducted where the LWC of the cloud has
 473 been modified while keeping the tunnel temperature, wind speed and droplet
 474 size constant at respectively -5°C , 50 m.s^{-1} and $20\ \mu\text{m}$. Five different values
 475 of LWC have been tested from 0.4 to 0.8 g.m^{-3} . Microstructure has been
 476 studied at a LWC of 0.4 g.m^{-3} and 0.7 g.m^{-3} only. Therefore the value of
 477 the grains size has been estimated for the other LWC from the known val-
 478 ues. Grains have been found to double in size from $225\ \mu\text{m}$ at a LWC of
 479 0.4 g.m^{-3} to $522\ \mu\text{m}$ at a LWC of 0.7 g.m^{-3} . In the absence of microstruc-
 480 ture observations at each LWC value and of any trend of behaviour of grains
 481 size with LWC, a linear fit was assumed between these two values and ex-
 482 trapolated for the LWC at 0.8 g.m^{-3} . As this hypothesis could be wrong
 483 and therefore mislead the results in terms of peak shear strength, the aver-
 age shear strength will also be presented and discussed here (figure 9). As

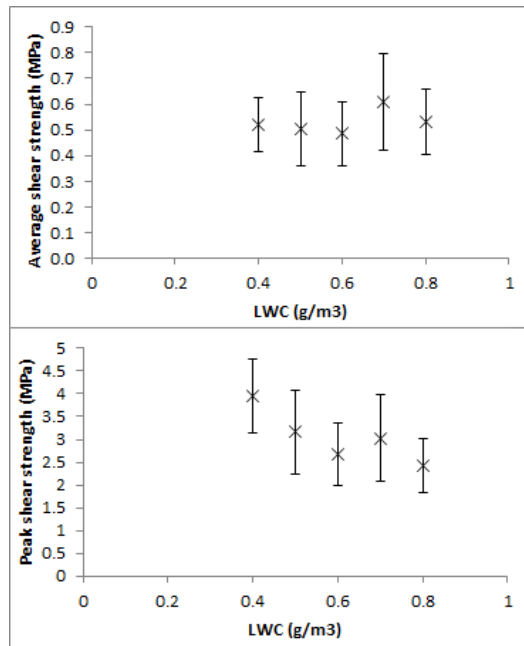


Figure 9: Effect of LWC on the shear strength of ice ($T=-5^{\circ}\text{C}$, $V=50\text{ m.s}^{-1}$, $\text{MVD}=20\ \mu\text{m}$)

484 shown on figure 9, the average shear strength was quasi independent of LWC
 485 whereas the peak shear strength was decreasing as the LWC increased. From
 486 equation 7, with a similar value of critical pressure, larger grains size leads
 487

488 to lower value of peak shear strength hence the trend observed. Druetz et
 489 al. [6] conducted experiments with two different LWC and droplet size. He
 490 reported that an increase in this combination of parameters resulted in an
 491 increase in the adhesive shear strength. The same kind of observation was
 492 made by Petrenko [15] who concluded that adhesive shear strength increases
 493 with LWC in the range from 0.3 to 2.4 g.m⁻³. In these two studies, the wind
 494 velocity used was much lower than in the present experiments (between 8
 495 and 20 m.s⁻¹ for Druetz, 20 m.s⁻¹ for Petrenko and 50 m.s⁻¹ for this study).

496 6.3. Influence of tunnel wind speed

497 In the same way as for the previous parameters, the tunnel wind speed
 498 has been modified while the temperature, the LWC and the droplet size were
 499 kept constant at respectively -5°C, 0.4 g.m⁻³ and 20 μm. Different values
 have been tested from 50 to 80 m.s⁻¹ (figure 10). The average shear strength

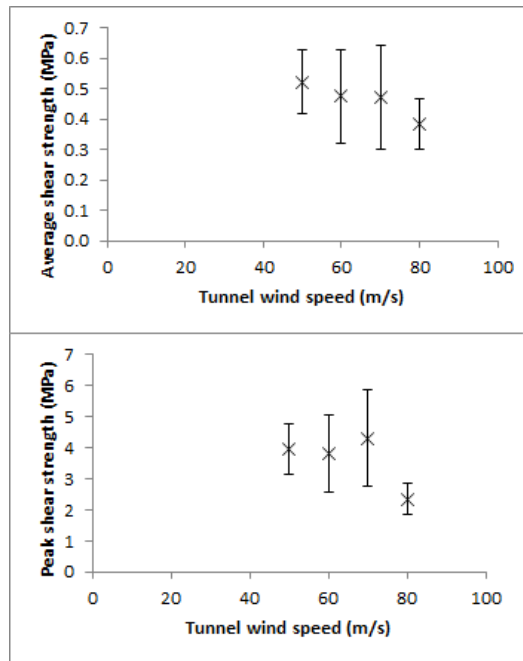


Figure 10: Effect of tunnel wind speed on the shear strength of ice

500 has been found to decrease from 0.52 MPa to 0.38 MPa as the tunnel wind
 501 speed increased from 50 to 80 m.s⁻¹. The trend of the peak shear strength
 502 is less obvious. A maximum seemed to appear at 70 m.s⁻¹ followed by a
 503

504 drop to 80 m.s^{-1} . More data would be needed to have a better view of the
 505 behaviour of peak shear strength with tunnel wind speed.
 506 Druetz et al. [5] reported an increase of shear strength with speed from 4 to
 507 16 m.s^{-1} which level up until 20 m.s^{-1} . Chu and Scavuzzo [7] also found a
 508 small increase of shear strength with speed between 20 and 90 m.s^{-1} but the
 509 trend was not clear due to scatter.

510 6.4. Influence of surface roughness

511 The aforementioned mechanical tests have been carried out on well polished
 512 titanium. Some preliminary work of the effect of the substrate surface
 513 finish has been made by finishing the titanium surface with coarse grinding
 514 paper. This results in the appearance of groves in the horizontal or vertical
 direction (figure 11). No microstructure observations have been made for

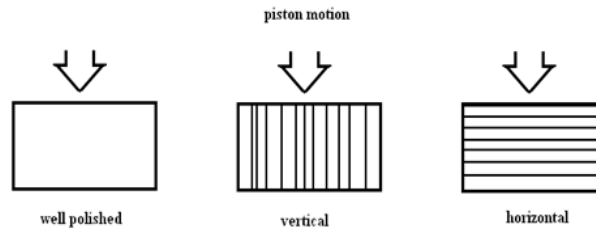


Figure 11: Representation of the different roughness on the substrate surface

515 the ice accreted on these surface so, in order to compare the influence of
 516 substrate surface roughness, the average adhesive shear strength will be used
 517 in this section.
 518

519 In general, the adhesive shear strength was seen to increase as the roughness
 520 increases and higher values have been found for the horizontal stripes rather
 521 than for the vertical stripes. On figure 12, the numbers (500, 800 and 1200)
 522 represent the grit of the silicone carbide paper and the letters, V and H,
 523 stands for vertical and horizontal respectively as shown on figure 11.

524
 525 The increase in shear strength with the roughness was expected as the ice
 526 is assumed to stick more to a rough surface than a smoother surface. In the
 527 case of shear especially, ice is thought to slide more easily when accreted on
 528 a smoother surface.

529 The authors who have studied the effect of surface roughness reported an
 530 increase in adhesive shear strength as the roughness increases up to a certain

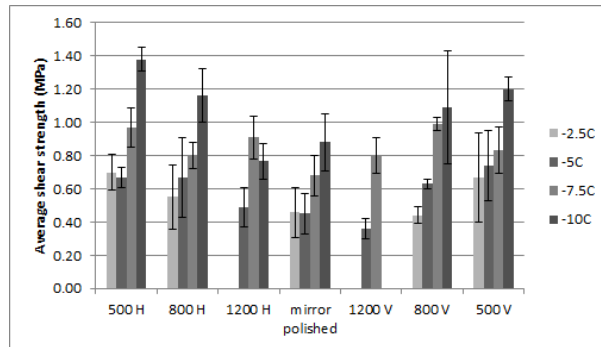


Figure 12: Effect of substrate roughness on the adhesive shear strength of ice

531 value at which further increase in roughness has no influence on the adhesive
 532 shear strength [5, 7–9, 13].

533 7. Conclusion

534 Whilst many workers have reported ice adhesion strengths to various
 535 engineering surfaces, only few workers have done so for impact ice. The work
 536 published on impact ice comes from a diversity of test rigs and procedures
 537 each producing distinct thermal history and load transfer characteristics.
 538 To this range we add a new shear test rig which may be operated in icing
 539 conditions. It features a stress concentration to promote adhesive fracture
 540 and minimise the influence of ice thickness and any geometrical irregularities.
 541 The stress distribution has been analysed in terms of critical stress intensity
 542 K_{IIc}^* as a function of applied pressure for crack to grow. This has been
 543 applied, together with some information on the scale of the microstructure
 544 to produce a shear strength.

545 The test has been used to illustrate the dependence of shear bond strength of
 546 impact ice to a Ti-6Al-4V alloy sheet material on the temperature at which
 547 the ice forms and is tested, cloud concentration, wind speed and surface
 548 roughness. The trends observed when the ambient temperature was varied,
 549 were similar to those reported by other workers but the shear strength values
 550 were significantly greater taking this peak stress approach.

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554 **References**

- 555 [1] Hobbs P.V. (1974) Ice Physics. Oxford
- 556 [2] Stallabrass J.R., Price R.D. (1962) On the adhesion of ice to various
557 materials. National research laboratories LR-350
- 558 [3] Fortin G., Perron J. (2009) Spinning rotor blade tests in icing wind
559 tunnel. AIAA 2009-4260, doi:10.2514/6.2009-4260
- 560 [4] Laforte C., Beisswenger A. (2005) Icephobic material centrifuge adhesion
561 test. IWAIS XI
- 562 [5] Druez J., Phan C.L., Laforte J.L., Nguyen D.D. (1979) Adhesion of glaze
563 and rime on aluminium electrical conductors. Transaction of the cana-
564 dian society for mechanical engineering 5:215-220, doi:10.1139/tcsme-
565 1978-0033
- 566 [6] Druez J., Nguyen D.D., Lavoie Y. (1986) Mechanical properties
567 of atmospheric ice. Cold Regions Science and Technology 13:67-74,
568 doi:10.1016/0165-232X(86)90008-X
- 569 [7] Chu M.C., Scavuzzo R.J. (1991) Adhesive shear strength of impact ice.
570 AIAA journal 29:1921-1926
- 571 [8] Scavuzzo R.J., Chu M.L., Kellackey C.J. (1996) Structural analysis and
572 properties of impact ices accreted on aircraft structures. NASA CR-
573 198473
- 574 [9] Scavuzzo R.J., Chu M.L. (1987) Structural properties of impact ices
575 accreted on aircraft structures. NASA CR-179580
- 576 [10] Millar D.M. (1970) Investigation of ice accretion characteristics of hy-
577 drophobic materials. report no. FAA-DS-70-11
- 578 [11] Blackburn C., Laforte C., Laforte J.L. (2000) Apparatus for measuring
579 the adhesion force of a thin ice sheet on a substrate. 9th international
580 workshop of atmospheric icing of structures
- 581 [12] Javan-Mashmool M., Volat C., Farzaneh M. (2006) A new method for
582 measuring ice adhesion strength at an ice-substrate interface. Hydrol.
583 Process. 20:645-655, doi:10.1002/hyp.6110

- 584 [13] Laforte C., Laforte J.L. (2009) Tensile, torsional and bending strain at
585 the adhesive rupture of an iced substrat. Proceedings of the ASME 2009
586 28th international conference on ocean, offshore and arctic engineering
587 pp.79-86, doi:10.1115/OMAE2009-79458
- 588 [14] Brouwers E.W., Palacios J.L., Smith E.C., Peterson A.A.(2010) The
589 experimental investigation of a rotor hover icing model with shedding.
590 Annual Forum Proceedings - AHS International, 4, 2619-2635
- 591 [15] Petrenko V.F. (2006) In-situ study of physical properties and structure
592 of atmospheric ice. report no.45042-EV
- 593 [16] Jayatilaka A. (1979) Fracture energy of engineering brittle materials.
594 Applied science publishers LTD
- 595 [17] Anderson T.L. (2017) Fracture mechanics: Fundamentals and applica-
596 tions (4th edition). CRC Press
- 597 [18] Johnson K.L. (1985) Contact Mechanics. Cambridge University Press,
598 doi:10.1017/CB09781139171731
- 599 [19] Pervier ML.A. (2012) Mechanics of ice detachment applied to turboma-
600 chinery. PhD thesis Cranfield University
- 601 [20] Bogy (1971) Two edge-bonded elastic wedges of different materials and
602 wedge angles under surface tractions. Journal of Applied Mechanics
603 38(2):371-386, doi:10.1115/1.3408786
- 604 [21] Ashby M.F., Gandhi C. and Taplin D.M.R. (1979) Fracture-mechanism
605 maps and their construction for f.c.c metals and alloys. Acta Metallur-
606 gica 27(5):699-729, doi:10.1016/0001-6160(79)90105-6
- 607 [22] Cottrell A.H. (1989) Strengths of grain boundaries in pure
608 metals. Materials Science and Technology 5(12):1165-1167,
609 doi:10.1179/mst.1989.5.12.1165
- 610 [23] Ashby M.F. and Hallam S.D. (1986) The failure of brittle solids con-
611 taining small cracks under compressive stress states. Acta Metallurgica
612 34(3):497-510, doi:10.1016/0001-6160(86)90086-6
- 613 [24] Sutton A.P. and Balluffi R.W. (1995) Interfaces in Crystalline Materials.
614 Oxford University Press

615 [25] Pervier M.L.A., Pervier H., Hammond D.W. (2017) Observa-
616 tion of microstructures of atmospheric ice using a new replica
617 technique. *Cold Region Science and Technology* 140:54-57,
618 doi:10.1016/j.coldregions.2017.05.002

A new test apparatus to measure the adhesive shear strength of impact ice on titanium 6Al-4V alloy

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