SERIOUS INCIDENT

Aircraft Type and Registration:	Evolve Dynamics Sky Mantis	
No & Type of Engines:	4 Electric Motor Engines	
Year of Manufacture:	2020 (Serial no: LINCS 2)	
Date & Time (UTC):	1) 14 January 2021 at 1100 hrs 2) 17 February 2021 at 0930 hrs	
Location:	1) Skegness, Lincolnshire 2) Skegness, Lincolnshire	
Type of Flight:	Commercial Operations	
Persons on Board:	Crew - None	Passengers - None
Injuries:	Crew - N/A	Passengers - N/A
Nature of Damage:	1) Moderate damage to landing gear, fuselage and a motor. One blade missing 2) Moderate damage to landing gear and propellers. One blade missing	
Commander's Licence:	1) Other 2) Other	
Commander's Age:	1) 38 years 2) Unknown	
Commander's Flying Experience:	1) 14 hours (of which 2 were on type) Last 90 days - 5 hours Last 28 days - 5 hours 2) 9 hours (of which 2 were on type) Last 90 days - 2 hours Last 28 days - 2 hours	
Information Source:	Aircraft Accident Report Form submitted by the pilot	

Synopsis

A screw which attached the propeller blade of a UA to the motor hub adaptor failed during a training flight. A second screw failure was experienced by the same operator after the UA had been repaired and had been fitted with a different design of hub adaptor and screws.

The first failure was caused by stress corrosion cracking possibly with the presence of hydrogen embrittlement. The second was a fatigue failure which may have been initiated and accelerated by hydrogen embrittlement. The hardness of both screws exceeded the specification which increased the susceptibility of the screws to hydrogen embrittlement.

The UAS manufacturer has introduced several design changes to prevent reoccurrence.

History of the flight

14 January 2021 Accident

The pilot was operating the UAS on a familiarisation flight with an instructor and observer present. During a decent to landing, an unusual noise was heard, and a part was seen to depart from the UA when it was at approximately 10 m agl. The UA yawed to the left and fell to the ground. An initial inspection of the UA by the operating team revealed that the screw attaching one of the blades to a motor hub adaptor had fractured. A piece of the threaded part of the screw remained in the motor hub adaptor plate, but the remainder of the screw was not recovered. The blade was recovered approximately 20 m from the UA.

Following the accident, the manufacturer repaired the UA and changed all the motor hub adaptors to a different design. The motor hub adaptor had been subjected to approximately 1.16 million motor revolutions when the failure of the screw had occurred.

17 February 2021 Accident

A different pilot was performing a training flight under supervision with the same UAS. The UA was held in 'loiter mode' at about 100 m agl and about 120 m from the pilot. Whilst observing through the onboard camera, he noticed a change in motor sound and saw the video image wobble. He looked up to see the UA wobble, drop a distance and then wobble again. The pilot operated the return to launch site function and then the ascend control, but there was no response from the UA, which continued to descend until it struck the ground.

The UA was recovered approximately 170 m from the launch point with one of the propeller blades from the rear left motor missing, along with part of the retaining screw. Neither item was recovered. The threaded part of the screw and a jam nut were still attached to the motor hub adaptor. The manufacturer estimated that 3.6 million motor revolutions had been completed since the repair.

Aircraft information

The Evolve Dynamics Sky Mantis is a remote operated UAS designed for the emergency services sector (Figure 1). Lift and propulsion are from four electric motors mounted at the end of fuselage arms which drive two-bladed propellers. The propeller blades and fuselage arms can be folded to facilitate storage. The maximum motor speed is 9,500 rpm, however 2,500 to 4,500 rpm is typical for most operations.

Figure 1
Evolve Dynamics Sky Mantis

Two different motor hub adaptor designs have been used; the adaptor fitted at the time of the January accident was designed by the UAS manufacturer (type 1) and this was subsequently changed to an adaptor designed and supplied by a third-party manufacturer (type 2).

Type 1 - UAS Manufacturer motor hub adaptor

Each propeller blade is attached to the hub adaptor by a single M3, zinc plated, class 12.9 steel, socket head, shouldered cap screw. The 12 mm long screw is fastened into the threaded lower plate and secured with a split pin which engages with the castellations in the upper plate. Two further screws with split pins attach the adaptor to the motor. Washers are used to protect the composite blade (Figure 2).

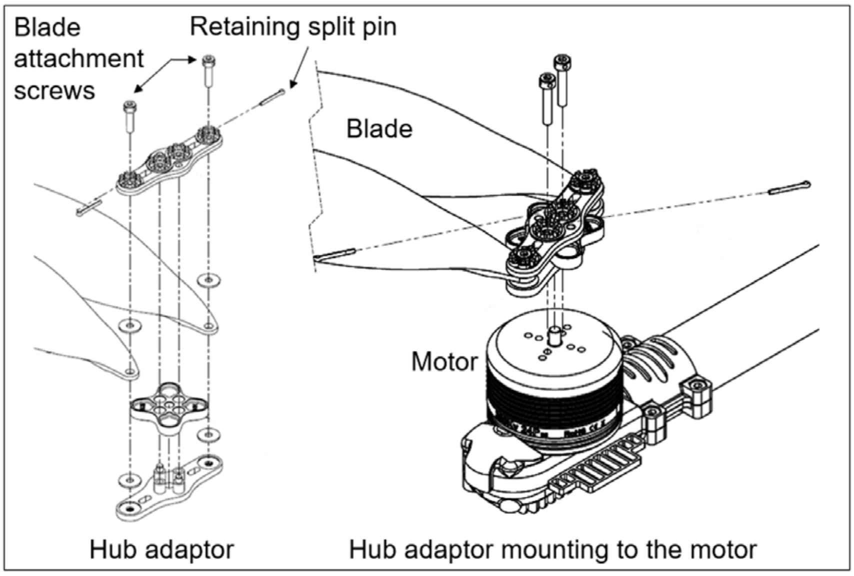


Figure 2
Type 1 Motor hub adaptor

Type 2 - Third party motor hub adaptor

The type 2 motor hub adaptor is similar in design except that it uses a jam nut underneath the lower plate, lock washers and thread lock compound to retain the propeller blade screw. The M3 screw is also made from class 12.9 steel however, it has a black oxide finish (Figure 3).

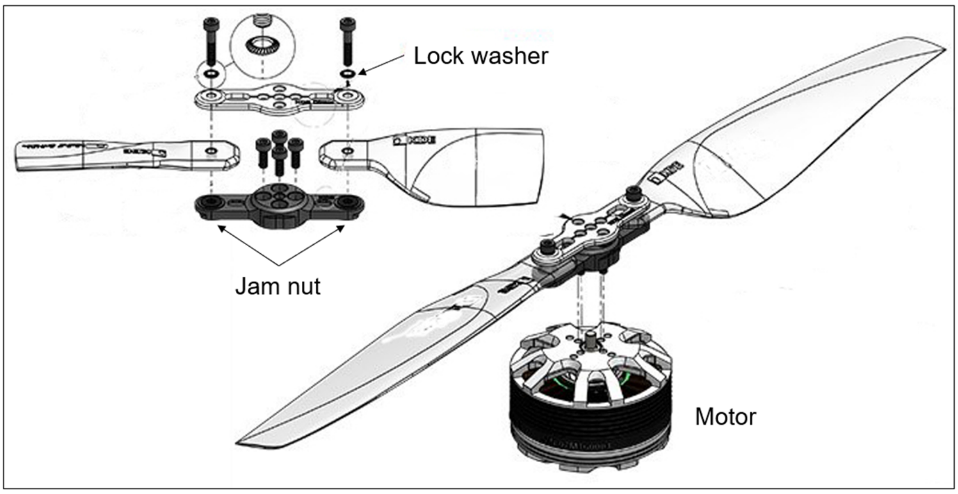


Figure 3
Type 2 Motor hub adaptor

Aircraft examination

The failed blade attachment screws were examined by a specialist metallurgist under an optical microscope up to x45 magnification and a scanning electron microscope up to x5,000 magnification, to determine the failure mechanism.

Type 1 - UAS Manufacturer motor hub adaptor

The screw had failed at the second thread from the plain diameter, (Figure 4) and the cut thread profile showed no material defects which would have initiated the failure. The fracture surface was intergranular, consistent with Stress Corrosion Cracking (SCC) with radial marks denoting the direction of crack propagation. There was light oxidation of the fracture surface, consistent with the relatively short period of service. The characteristics of the fracture face could not preclude the possibility that Hydrogen Embrittlement (HE) had also contributed to the failure mode.

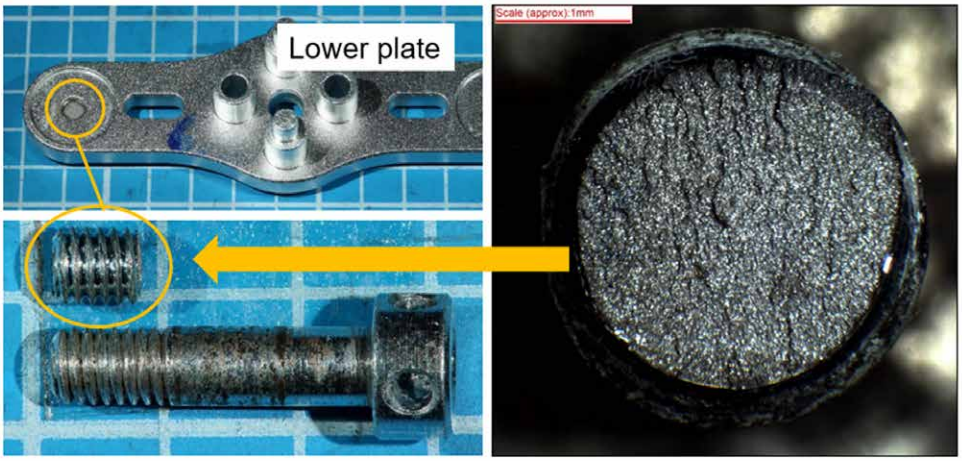


Figure 4
Type 1 Blade attachment screw, fracture face

Type 2 - Third party motor hub adaptor

The predominant failure mode of the type 2 screw was through fatigue, which initiated from the thread root and had propagated across 90% of the cross section before final separation occurred. No initiating defect could be identified however, approximately 20% of the stable crack growth cross-section exhibited evidence of intergranular fracture, consistent with hydrogen embrittlement. The remainder being trans-granular indicative of fatigue crack growth. The level of embrittlement was determined to be insufficient to have caused the failure however, it may have reduced the threshold for crack initiation and would have accelerated the crack growth.

Figure 5
Type 2 Blade attachment screw, fracture face

Tests and research

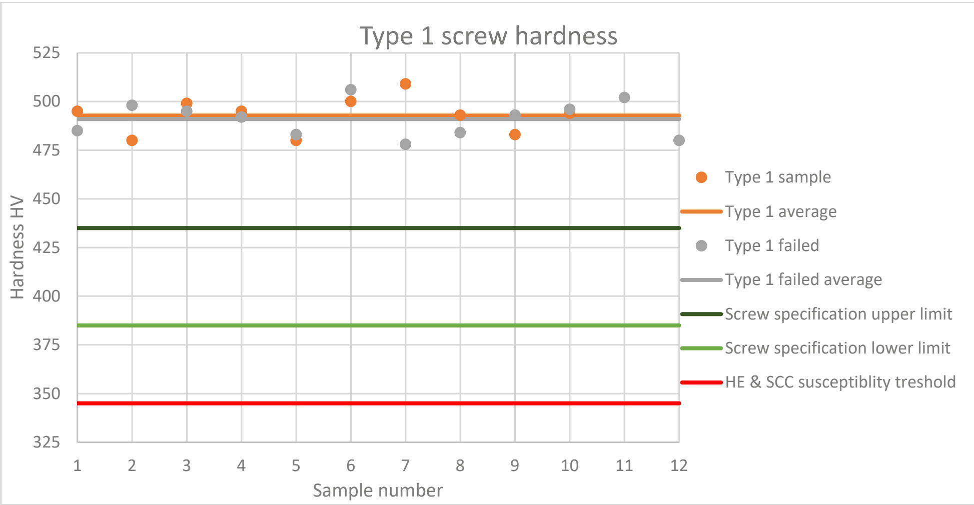
Hardness testing

Ten screws of each type were selected at random by the manufacturer and tested for hardness by an independent test facility to ASTM E92-17, Standard Test Methods for Vickers

Hardness of Metallic Materials. The remains of the two failed screws were also subjected to the same testing. The material specification is steel to BS EN ISO 898-1:2013 12.9 and the Vickers Hardness range for this steel is 385 HV to 435 HV, as shown by the two green bands in graphs 1 and 2. The red line in both graphs, denotes the hardness value (345 HV) above which steels become susceptible to both HE and SCC.

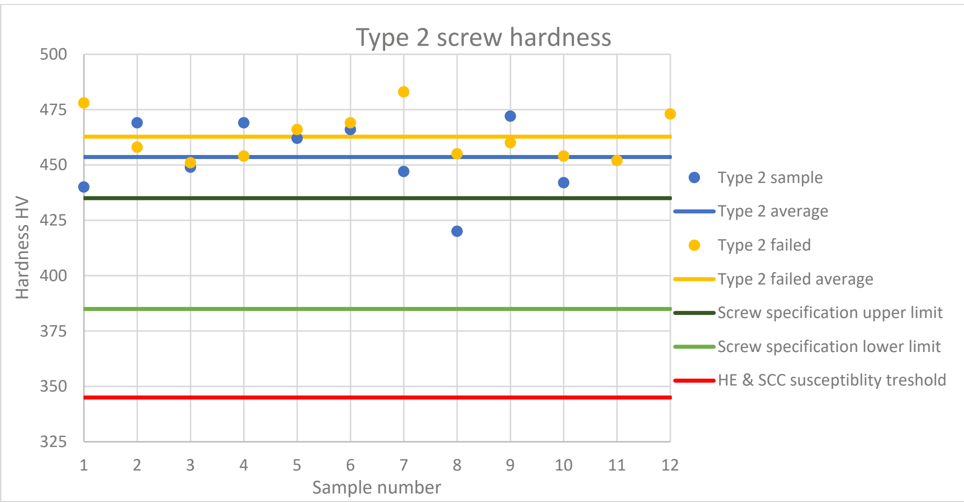
All the sample screws and the failed type 1 screw were very similar in hardness and exceeded the specification value. The difference between the average hardness of the sample screws and the failed screw was 2 HV.

Apart from one of the sample type 2 screws, all screws exceeded the hardness specification. The average hardness of the failed screw was almost 10 HV greater than that of the average hardness of the sample screws.



Graph 1

Hardness testing of type 1 screw samples



Graph 2

Hardness testing of type 2 screw samples

Manufacturer testing

Various pieces of video evidence taken by the UAS manufacturer were supplied to the AAIB showing several functional tests that had been undertaken to prove that the type 2 design could withstand operational loads under a variety of conditions. No test managed to replicate the failures seen during the accident flights.

Other information

Stress corrosion cracking

SCC is a stable crack growth mechanism that occurs when a suspectable alloy is subjected to a static stress in a corrosive environment. Heat treated low alloy (martensitic) steels are suspectable to SCC when the hardness exceeds 345 HV.

Hydrogen embrittlement

High strength steels susceptibility to HE increases with hardness, typically values exceeding 345 HV would invoke precautions to be taken during manufacturing. These might include de-embrittling the steel after a process step that may have introduced hydrogen, eg zinc plating. If hydrogen is present in the material, it is diffused within the crystalline lattice and it will concentrate at the points of highest residual or applied stress. This concentration changes the properties of the material and can result in failure at lower than the predicted strength. For HE to occur it must be a susceptible material with hydrogen present and sufficient stress, either applied or residual. HE failures may occur anything from a few hours to several years after the absorption of hydrogen.

The details of the manufacturing steps for either screw could not be obtained.

Design changes

In response to the two failures, the UA is now supplied with type 2 motor hub adaptors but with M4 screws. Single use locking nuts and shakeproof washers are used instead of the previously used thread locking compound. The assembly process is more detailed and controlled and a brass spacer bush has been fitted into the composite propeller blade root. Random sampling to test for hydrogen embrittlement has now been incorporated in the manufacturing process.

Further design changes are under consideration which include changing the screw material from class 12.9 steel to a corrosion resistant steel with a lower yield strength.

Analysis

Type 1 Accident

The primary failure mechanism for the type 1 screw was considered to be stress corrosion cracking but a contribution by hydrogen embrittlement could not be discounted.

The UAS was being operated near the coast and hence the saline content in the air may have provided an environment conducive for SCC. Radial markings indicated that a crack had initiated on the surface, in the root of a thread and propagated across the diameter and the entire fracture surface area was intergranular in nature. Hydrogen may have been present as a result from the zinc plating process due to ineffective de-embrittlement. The complete coating of the screws with zinc would have trapped the hydrogen in the part and therefore not allowed a path for it to escape. The screw was susceptible to both HE and SCC as it was significantly above the threshold of 345 HV and it also exceeded the hardness specification value.

The stress on the screw would have been a combination of flight loads on the blade and the axial preload as the screw was tightened. Testing done by the manufacturer has demonstrated that the screws can withstand all the operational loads in combination with the tightening torque.

Type 2 Accident

The failure of the type 2 screw was predominately fatigue crack growth but with areas of the fracture surface exhibiting hydrogen embrittlement. No initiating flaw could be identified but it is possible that stress concentration at the thread root in combination with HE was sufficient to initiate a crack which then grew during the 3.6 million motor revolutions before failure. It is possible that the application process for the surface finish was the source of hydrogen in the screw. The high hardness of the material would have reduced the fracture toughness and in combination with the HE further reduced the time to failure.

Design changes

The UAS manufacturer primarily changed the diameter of the screw from M3 to M4 as a solution to the failures. Whilst this gives an increase in cross sectional area and therefore extends the mean time to failure, no changes were made to the screw material or the manufacturing processes. The use of class 12.9 steel screws with the hardness values exceeding the specification was determined to be a causal factor in the failures. It was determined that if the screws had a greater fracture toughness and had hydrogen not been present then neither failure might have occurred.

Conclusion

The type 1 screw failure was probably driven by the operational environment and the presence of hydrogen within the very hard steel. This combination resulted in stress corrosion cracking possibly exacerbated by hydrogen embrittlement.
The type 2 screw failure by fatigue crack growth was probably initiated and then accelerated by hydrogen embrittlement.

The use of screws in both accidents with the hardness exceeding the specification value, was determined to be a causal factor in their failures.

Safety actions

As a result of these two events the manufacturer has made several design changes to the motor hub adaptor.

The UAS manufacturer has reviewed the design of the motor hub adaptor and made the following changes:

- Increased the screw diameter to M4
- Incorporated a stress test to ensure that bolts do not suffer from hydrogen embrittlement
- Used a serrated washer
- Used a single use lock nut
- Removed the thread locking compound
- Added a brass spacer to the blade root