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SOLUTIONS TO HELICOPTER BLADE EROSION
~ IMPROVING AIRCRAFT AVAILABILITY AND REDUCING COSTS

Pat Collins, Science Gateway, Helicopters Operating Centre, Defence Equipment & Support, Bristol, UK
Chris Moore, Materials Engineer, AgustaWestland, Yeovil, UK

Abstract

Helicopters engaged in military operations conduct a large number of take-offs and landings in “brownout” conditions. “Brownout” is a result of surface particles such as dust and sand being stirred up by the downwash from helicopter rotor blades causing a large cloud which can completely envelop the platform. Flying in “brownout” conditions can impact operational effectiveness in a number of ways including; loss of aircrew spatial awareness, damage to the helicopter in the form of erosion (particularly the engines and rotor blades) and scintillation from particle impacts with the rotor blades that creates a bright light source reducing the effectiveness of night vision devices.

This paper concentrates on activities to reduce the effects of operation in “brownout” conditions on rotor blades. The study initially concentrated on characterising the type of damage caused to blades by operating in sand/dust environments with a number of damage mechanisms being identified. Maintenance records for the majority of helicopter types in UK service were interrogated with the results indicating that damage to blades from operation in sand/dust environments is a significant problem. The cost of reworking severely damaged blades has been quantified and is considerable, generally requiring that the blades are returned to the manufacturer for an extended period of time. A range of protection technologies were identified which largely mitigate blade erosion. Whilst work continues to investigate and develop new solutions it has been concluded that at present blade tape that is maintained effectively provides the most cost effective solution for UK military helicopters.

To support the selection of future materials; a dynamic test facility has been developed which will allow samples of candidate mitigations to be tested in a representative sand/dust environment. The facility is novel in that it provides the capability to test a number of samples simultaneously ensuring that all of the materials are subjected to a similar level of damage. This approach will allow a simple comparison to be made between known “best of breed” solutions with new candidates.

1. INTRODUCTION

1.1 Military Helicopter Operations within the UK

The UK MOD operates a fleet of more than 400 helicopters[1] of many different types providing a range of capabilities that can be categorised as Lift (transport of people and equipment), Find (reconnaissance) and Attack. These are operated by all three services (Army, Royal Air Force and Royal Navy) with some overlap of tasking between the services. A revised strategy agreed through the 2010 Strategic Defence and Security Review (SDSR) aims to reduce the number of different types in service, with an aspiration to reduce to five core types by 2020. This will see the introduction of new helicopters (Chinook and Wildcat), upgrading of some existing types (Apache, Chinook, Merlin and Puma) and retirement of others (Gazelle, Lynx and SeaKing).

In addition to the core fleets there are a number of other helicopter types used to support a range of training, liaison and other roles.

1.2 Operational Environment

Helicopter operations and training takes place in a very wide range of locations ranging from Bardfoss in Northern Norway to El Centro in Southern California exposing helicopters to extremes of temperature and potentially damaging particulates in the form of sand, dust, rain and snow. El Centro provides the opportunity to operate in a fully immersive, live range environment that closely matches that encountered in Afghanistan.

Since 2001 the UK has been involved in operations in Afghanistan and Iraq in desert conditions that are extremely dusty. Whilst some of our helicopters routinely operate from prepared landing strips, the Apache attack helicopter being an example; a significant percentage of the fleet regularly land in and take off from remote patrol bases where no surface preparation has been carried out. These austere, generally forward, locations result in helicopters regularly encountering “brownout” conditions. “Brownout” is a result of surface particles such as dust and sand being stirred up by the downwash from the helicopter rotor blades causing a large cloud which can completely envelop the platform, as illustrated in figure 1. The nature of the dust cloud can vary significantly depending upon the size of the particulates.

Figure 1: Merlin helicopter engulfed in dust cloud (image courtesy of www.defenceimagery.mod.uk)

1.3 Operational Impact

Flying in "brownout" conditions can impact operational effectiveness in a number of ways:

- Loss of aircrew spatial awareness when taking off and landing which can lead to uncontrolled impacts with the ground;
- Damage to the helicopter from erosion, particularly the engines and rotor blades;
- Scintillation from particle impacts with the rotor blades creating a light source and reducing effectiveness of night vision devices.

Considerable work has been undertaken to develop technological solutions to permit safe operation of helicopters in brownout conditions. This work is continuing with the goal of fielding a robust and affordable solution at the earliest opportunity. Some information on the UK programme was presented in my paper at a previous ERF[1]. Studies also continue to identify enhanced filtration techniques to provide a higher level of protection to the engines.

This paper concentrates on work carried out in the UK over the past two years to reduce the erosion damage caused to rotor blades from operation in sand and dust. The solutions considered also go a long way to reduce blade scintillation.

1.3.1 Blade Erosion

Helicopter Rotor Blades generally consist of a load bearing spar forward section with a light weight aerodynamic rear section. In most helicopters the spar is made from composite material (generally carbon/epoxy or a hybrid of glass and carbon/epoxy) which although very strong and stiff is prone to damage from impact with sand, dust, snow, rain etc. The general means of providing impact damage protection for the spar is to add a hard metal layer to the leading edge of the blade generally termed as an "erosion shield". Typical materials used for this sacrificial layer are titanium, nickel and corrosion resistant steel. The primary concern in the past has been to provide a robust solution to allow operations in rain, a typical metallic erosion shield is considered to need replacement after 3000 flying hours.

Operation in sand and dust environments provides a much more aggressive level of erosion to the blade than rain which can result in severe damage occurring to the erosion shield in a relatively low number of flying hours. In order for crews to operate effectively in theatre it is essential that sufficient pre-deployment training is carried out in a representative environment. A significant amount of time is spent on practicing take-offs and landings in a sand and dust environment, this results in considerable damage to the rotor blades from erosion.

In many cases the damage caused to the rotor blades tends to be limited to a polishing effect of the erosion shield where it becomes difficult to quantify the residual thickness. In extreme cases the erosion shield is reduced to a very thin foil which without detailed inspection can fail without warning to the operator, see figure 2, leading to damage to the substrate and immediate unserviceability.

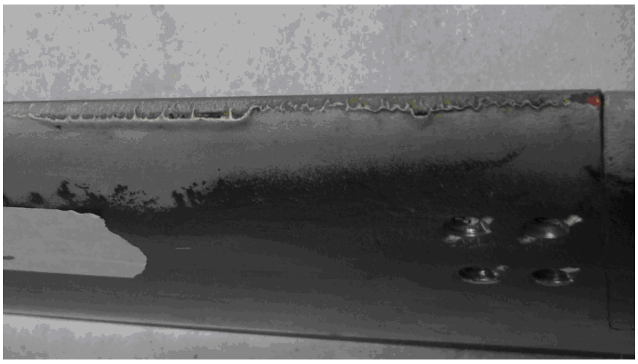

Figure 2: Tail rotor blade showing severe erosion and perforation of the leading edge. (image courtesy of AgustaWestland)

Erosion is not confined to the erosion shield/leading edge area of the blade however, effects such as the constant change of pitch of the blade and the high air pressure under the blade result in erosion away from the leading edge of the blade which could become significant if left unattended to, see figure 3. The structure of the blade aft of the spar tends to be of much lighter construction with thin composite skins generally carbon/epoxy or glass/epoxy) and a foam or honeycomb trailing edge filler.

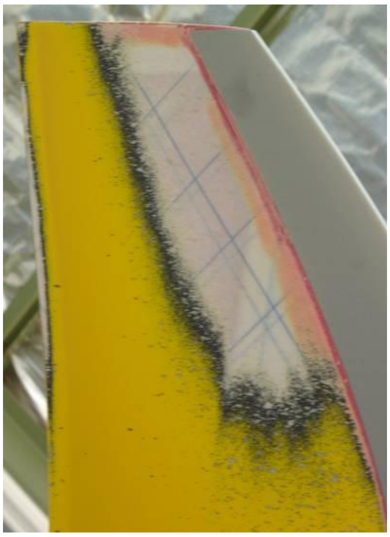

Figure 3: Sand erosion damage on an AW-139 Main Rotor Blade (image courtesy of AgustaWestland)

1.3.2 Scintillation

Scintillation (also sometimes referred to as the “Kopp-Etchells effect”) is a term used to describe the light generated around rotor blades as they are engulfed in dust, see figure 4. The primary cause of the phenomena is the oxidation of material from the leading edge erosion shield of the blade following impact from sand and dust particles. The brightness of the light generated is dependant upon the material used for the erosion shield with titanium demonstrating the highest intensity although similar effects can be seen with other materials[2].

A secondary effect is caused by the fracto-luminescence of particles of sand and dust. This is considerably less intense than the primary source but is dependant upon the dust rather than the construction of the rotor blade.

Figure 4: Chinook helicopter demonstrating scintillation (image courtesy of Michael Yon, www.michaelyon-online.com)

2. TECHNICAL PROGRAMME

2.1 Overview

In order to gain a greater understanding of the issues relating to blade erosion the Materials and Structures Technology - Science and Technology Centre (MAST STC) placed a contract on AgustaWestland, Yeovil to conduct a study, the main activities were:

- Gain a thorough understanding of the damage mechanisms
- Collect data on damage sustained during operations and in pre-deployment training
- Review available mitigation technologies
- Provide cost information on the mitigation options including a “do nothing” option
- Develop a Test Facility suitable for assessing the performance of future mitigations

2.1 Characterisation of the Erodent

To understand the types of erodent that the helicopter might encounter in service three soil samples were taken from different locations in a representative country covering the range of terrain the helicopters might be required to operate in. The sand samples consisted of a typical unprepared landing strip, fine sand and coarse sand. The sand was sifted to determine particle size and examined under a microscope to determine surface morphology, as shown in figure 5. Particle size associated with traditional sand found on the South Coast of the UK has also been plotted for comparison (defined as the Modified Redhill Mix[3]).

The initial finding from analysing the samples is the wide ranging variety of particles present. The sample from an unprepared landing strip showed a low proportion of small particles present and a large number of small stones measuring in excess of 1000µm, these larger stones were irregular in size with jagged edges. The fine sample consisted of dust, with an average grain size of approximately 54µm. The UK MOD define this dust as ‘temporarily airborne dust’ and can remain in suspension in the atmosphere for extended periods of time by the natural turbulence of the air. Coarse samples contain similar size sand as that associated with the British coast, represented by the Modified Redhill mix in figure 5. Upon further investigation the sand consisted of smoothed particles with an average diameter of 200µm. Particles of such dimensions are classified as instantaneously airborne dust by the UK MOD and as a result of their mass are most commonly raised by artificial means.

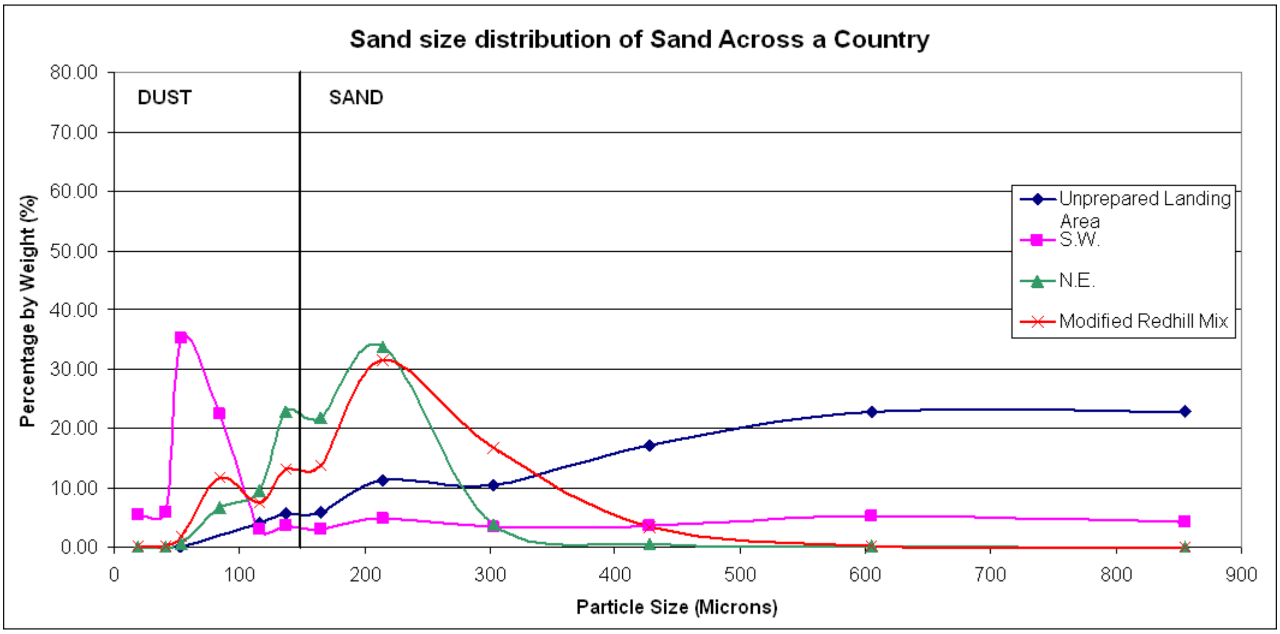

Figure 5: Sand size distribution (image courtesy of AgustaWestland)

Investigation of the sand particles; excluding those greater than 850µm illustrates that the sample taken from the unprepared landing strip consists of particles covering a wide range of dimensions, as visible in figure 5. This sample can be broadly characterised as containing two separate groups of particles, one being largely composed of coarse dust/sand and the other of small stones.

The three sand types identified above present their own unique problems:

- Temporarily airborne dust particles pose a number of problems as their hard nature means they can cause erosion to exposed surfaces. The low size and mass of these particles means that they can infiltrate any cavity of an aircraft resulting in abrasive wear between sliding surfaces.
- The coarser sand, such as that found in the North East of the country results in abrasive wear of exposed surfaces of the rotorcraft with the rate of erosion dependent upon the velocity of particulate relative to the surface. The high velocity of rotor blades makes them highly susceptible to erosive wear.
- The small stones, such as those found on the unprepared landing strip are unable to be raised by natural means. Powerful air flows such as rotor downwash from low level operations would be capable of raising such small stones, leading to the possibility of impingement with the rotor disk.

2.2 Erosion Theory

In flight, the airflow generally impinges the blade at 90° to the blade nose and flows around the nose to the trailing edge. Consequently erosion shields have to be capable of resisting a 90° solid particle impact, whilst the particle flow around the leading edge means that the shield will also experience particle impingement at all angles including 0°. In addition, effects such as the constant change of pitch of the blade and the high air pressure under the blade result in wear away from the leading edge of the blade.

The rate of sand erosion on a material depends upon a large number of factors including the material properties, those of the substrate material, the nature of the bond between the two and the size, shape and hardness of the erodent and speed.

The rate at which an erosion shield is worn away is predominantly dependent upon the angle of incidence and the material behaviour of the erosion shield. At low impact angles the dominant wear process is a ductile one as the erodent particles gouge material off of the surface[4]. This results in high erosion rates for ductile materials and lower rates for brittle materials.

Conversely at impact angles closer to 90°; the failure mode is dominated by brittle erosion. The theory is that as the particle impacts it generates fine cracks on the surface, with material loss occurring when the cracks intersect. Upon development of intersected cracks the final removal of the material depends upon the level of adhesion to the substrate and the angle of impingement of the particles. This brittle mechanism results in high erosion rates for brittle materials and a reduction in erosion rate approaching 90° for ductile materials as particles are likely to bounce off, see figure 6.

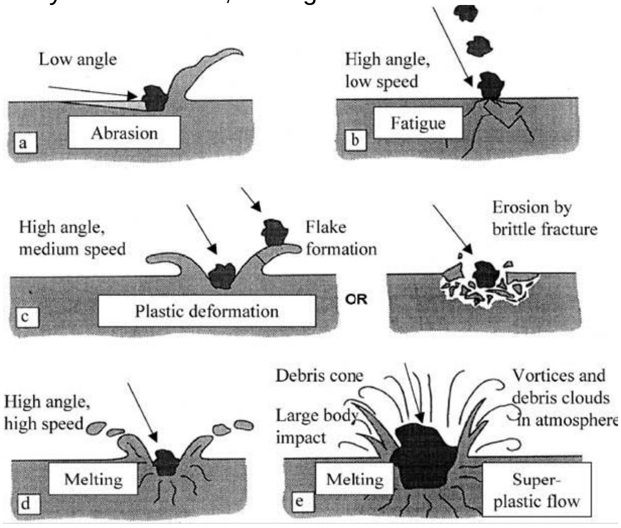

Fig 6: Possible Mechanisms of Solid Particle Erosion (image courtesy of University of Kaiserslautern)

3. IN SERVICE EXPERIENCE[5]

3.1 Overview

Data on the true impact of sand erosion on helicopter availability has historically not been collected in a coherent manner leading to only a partial understanding of the true benefits of mitigation solutions. It is often difficult to determine exactly where an eroded blade saw service and to associate its operational usage with the level of damage sustained by the time it is returned to the manufacturer for repair. A large amount of information as to the extent of sand erosion was based upon anecdotal feedback from the front line units.

3.2 Analysis of Available Data

To gain a thorough understanding of the effect of sand erosion on UK MOD helicopters an analysis was conducted of data provided by 1710 NAS (Naval Air Squadron) following analysis of aircraft databases including WRAM (Work Recording and Asset Management) and LITS (Logistics Information Technology System) covering the period from August 2007 to August 2011. During this period the UK MOD were engaged in combat operations in both Afghanistan and Iraq involving significant amounts of operations into and out of austere landing areas. Incidents for each aircraft were assessed as to whether the reported damage could be attributed to erosion

As erosion damage to the helicopters main and tail rotor blades was the focus of the investigation any entry specifically mentioning damage to regions of the blade except the leading edge region and tip cap was discounted as it was presumed that this was not attributed to solid particle impingement.

The analysis made no account for aircraft fleet numbers or relative operations undertaken. It was merely intended to give an initial understanding of the level of erosion experienced by each aircraft type and whether there were any specific issues. A future aspiration is to compare the damage reported with typical mission profiles in order to give a greater understanding of the damage reported.

3.3 Main Rotor Blade Erosion

Overall the findings show a large difference in erosion incidents reported between the different aircraft types as shown in figure 7. Support Helicopters such as the Lynx, Puma and Merlin were found to suffer significant damage that could be attributed to erosion. This is likely to be as a result of the large number of landings these aircraft make often on unprepared landing strips. This link with the number of landings is supported by analysing the level of erosion on the Apache blades which, despite operating alongside the Merlin, rarely landed on unprepared surfaces. Apache is often employed to provide surveillance meaning it is not generally required to operate away from main operating bases and subsequently is not frequently exposed to high levels of erodent.

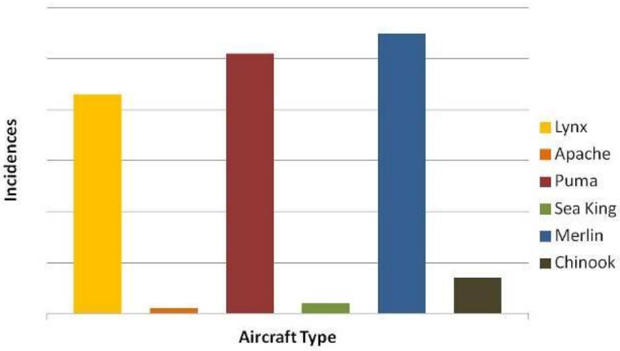

Figure 7: Reported Main Rotor Blade Erosion Incidents between August 2009 and August 2010 (image courtesy of AgustaWestland)

An anomaly in the data is the level of erosion incidents recorded for the Chinook fleet which, whilst operating in a similar role to the Merlin carrying stores & troops around the battle field, has levels of erosion significantly lower than that of the Merlin fleet. The low level of erosion experienced by the Chinook fleet is attributed to the increased level of maintenance applied to the rotor blades whilst on operations. Typically the Chinook blades were carefully inspected and repairs carried out to the blade tape after every flight, incurring a high maintenance penalty. The Sea King fleet in theatre was generally not exposed to an erosive environment in significant numbers during the period of operations covered by the data.

The high level of erosion was highlighted by in-service feedback where one aircraft was reported to have received 16 main rotor blades in 66 days and 15 tail rotor blades in 56 days around the same time. Whilst this is not quantifiable data, as there is no indication on the installed blades original eroded state, it does highlight the severe environments encountered by some aircraft and the need for an improved protection scheme for the aircraft.

3.4 Tail Rotor Blade Erosion

Analysis of data relating to the Puma Support Helicopter showing the number of erosion incidents relating to main and tail rotor blades are broadly indicative of the remainder of the support helicopter fleet. This indicated that the number of reported incidents for tail blades is significantly greater than for main blades. See figure 8.

A potential explanation of the difference is that the tail rotor is at a high level of incidence when in the hover (as would be the case when erosion is most likely to be encountered).

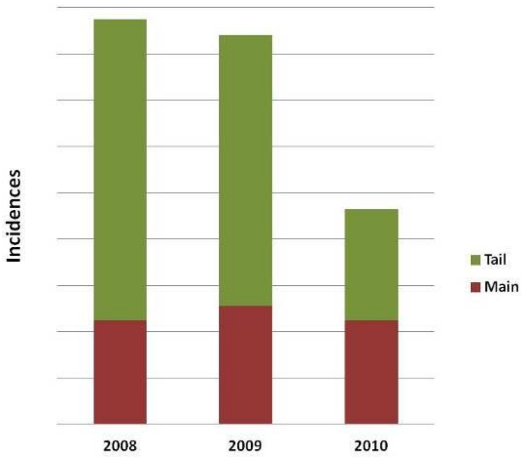

Figure 8: Reported Main and Tail Rotor Blade Erosion Incidents for the Puma fleet (image courtesy of AgustaWestland)

4. MITIGATION OPTIONS[6]

4.1 Overview

A number of options to reduce the damage caused by sand and dust on helicopter rotor blades have been considered including means of suppressing the formation of sand and dust clouds by surface treatment and/or the use of special matting. Whilst these measures were partially successful they did not provide a long term solution to operating from austere landing strips.

The following paragraphs concentrate on the provision of an “organic” solution to blade erosion concentrating on Paints, Tapes and Coatings. The relative merits of these options are given in table 1.

The repair designations used in the table are shown below

R1	Front Line
R2	Work Shop
R3	Contractor Work Party
R4	Return to Vendor

Table 2 provides an overview of the advantages and disadvantages of the most effective protection schemes; considered to be Tape Protection and Coatings.

4.2 Paint Protection

Paint protection has been the standard repair protection system employed by operators to protect all areas of the blade behind the leading edge. Restoration of the paint finish can be achieved in a number of ways from a complete re-spray in a blade repair bay, the use of sanctioned touch up kits or application of available paint aerosols. This method of protection is deemed inadequate as due to the thickness and poor erosion resilience repairs only occur to the blade once paint has been removed leaving the blade surface frequently exposed to damage. As such current ‘protection’ using paint merely retards erosion.

Paints are traditionally applied to the blade in order to protect it from environmental degradation and for aesthetic reasons; as such they traditionally offer limited protection to the blade from erosion. Paint mass is heavily controlled during construction in order to achieve satisfactory balancing of the blade. Therefore significant erosion to the blade could have an adverse effect on blade balance, as can local build up of applied paint can.

4.3 Tape Protection

Tape protection is defined by the use of pre-cured polymer that is secured on to the blade through either a self adhesive layer or a separate bonding process. The protection is relatively easy to apply (given appropriate training and a suitable working environment) and can, depending on the adhesive, be quickly removed should the aircraft’s role change or failure of a tape section occur; the blades can be quickly returned to their original state with no penalties. Tapes also have the added benefit that due to the method of manufacture and application it is relatively easy to calculate and control the additional mass and its distribution along the blade and the effect upon blade aerodynamics.

	No Protection	**Paint Protection**	**Tape Protection**	**Coating**
Application	N/A	Easy	Skilled	Specialist
Effectiveness	Rapid damage will occur	Temporary/Short term solution	Very Good	Very Good
Maintenance	R4/Beyond Economic Repair	R1/Requires regular maintenance; quick to apply	R1/Requires regular maintenance; skilled repair process	R1/Low initially; repair process requires high level of skill to apply correctly
Ease of Removal	N/A	R2/R4	R1	R4/Difficult
Cost - Initial	Zero	Low	Medium	High
Cost - Ongoing	Zero	Low	Medium	Low/Medium
Cost – Long Term	Expensive R4 repair or Beyond Economic Repair	Possible R4 Leading and Trailing Edge replacement, R4 Strip and repair	R2/R4 Strip & Repaint	R4 Strip and Repaint, if coating can be removed
Protection Summary	**Little or No Protection to Sand & Dust Erosion**		**Significant Protection to Sand & Dust Erosion**	

Table 1: Comparison of Main Organic Protection Options

	Advantages	**Disadvantages**
Tape protection	Maintenance can be carried out in situ	Can become detached in rain
	Tape replacement and initial fitting by skilled personnel increases durability	High frequency maintenance is required
	Role Fit	
	Rotor Aerodynamics and Dynamics maintained after tape repair/replacement	
Coating	Good initial durability	Permanent fit as difficult to remove once applied
	Low Initial maintenance	Robotic spray application required to maintain aerodynamic profile and dynamics
	Stone cut resistance	Effect of repair upon rotor dynamics and aerodynamics
		Current leading product was developed in US, ITAR implications

Table 2: Advantages and Disadvantages of the Most Effective Organic Protection Options.

Self adhesive tape requires very little equipment for application and can be applied to the blades either on or off the aircraft. Application consists of thoroughly cleaning the blade before carefully positioning the tape over the leading edge. Exposed edges of the tape are traditionally sealed in order to prevent moisture and air ingress. Feedback from in-service has highlighted the importance of the environment when applying the tape, tape applied off the aircraft in controlled environments has been found to offer greater performance than tape applied in service.

4.4 Coatings[7]

Sprayed coatings are a permanent solution to the issue of blade erosion and application requires specialist equipment and a climatic controlled room in order to apply the coating. Sprayed coatings offer a greater adhesion to the substrate than a bonded coating whilst the lack of edges means that the coating will not completely de-bond. Sprayed coatings are also often applied over the entire blade meaning that as well as the leading edge other areas are protected from erosion damage. Due to the permanent nature of the coating it provides an added level of complexity when carrying out blade maintenance and/or NDT operations.

There is some evidence to suggest that the addition of fillers to Polyurethane in order to improve erosion resistance can be beneficial.

Research into the addition of Alumina (Al_2O_3) into Polyurethane[8] to increase erosion resistance noted a number of features.

- The addition of Alumina increased the hardness with a converse affect on tensile strength.
- The Alumina was found to increase erosion resistance to sand slurry using a bespoke machine.
- The addition of Alumina was found to follow typical behaviour of filler addition by initially causing an increase in erosion resistance of Polyurethane up to approximately 20% by weight of filler.
- Further increasing the Alumina content was found to have a detrimental effect on erosion resistance at higher percentages.

4.4 Future Technologies

As well as additional materials adhered to the blade surface there is the possibility of enhancing the material surface properties through material deposition. The use of such deposition techniques could enhance the hardness of the metallic leading edge shield, testing undertaken by AgustaWestland has shown that such processes are able to offer small increases in solid particle resistance but no change to fluid particle resistance. The research highlighted the importance of carefully selecting deposition process and shield preparation technique to ensure optimum performance.

Ceramic deposition coatings are available which can be applied to metal or composite materials giving a ceramic layer typically between 50-300μm thick. Discussions with manufacturers have suggested that whilst damage to the coating could be repaired this would necessitate the component being returned to them. Research[9] suggests that brittle coatings would not be recommended for use on the blade nose however at angles below the nominal they are reported to offer excellent resistance to gouging particles. Discussions with potential suppliers have suggested that they are currently unable to consider application of the coating onto a Main blade due to restrictions imposed by the physical capacity of equipment to accommodate a blade.

In support of the Rotor Durability Army Technology Objective a programme of research was undertaken by the US Army Aviation Applied Technology Directorate (AATD) and Sikorsky Aircraft[10] which considered the use of a combination of tungsten carbide coatings on the blade leading edge coupled with a cold-sprayed Niobium coating on the leading edge substrate. The programme demonstrated the potential benefits of these coatings in a lab environment towards realising a 1000 hour life, proof of concept main and tail blades for UH-60 Blackhawk were planned for delivery for evaluation in 2011.

5. COST BENEFITS

Part of the programme was to provide cost information on the mitigation options considered and to compare that with the cost of doing nothing. AgustaWestland have conducted an analysis[11] which identifies the bought out costs, manpower costs and elapsed time for a number of these options. Commercial sensitivities limit the level of detail that can be presented here. In simple terms application of blade tape can be accomplished by a two man team in around one day at a fraction of the cost of replacing a metallic erosion shield. Typically the elapsed time from a blade being declared unserviceable to it returning to service following replacement of the erosion shield is around 6 months.

6. TECHNICAL PROGRAMME

6.1 Summary

In order to be able to assess the performance of alternative solutions a method for conducting representative testing under laboratory conditions was required. An assessment of existing test facilities (generally located in academia) in the UK was undertaken, this concluded that although all of them provided useful facilities none of them were ideally suited to this particular purpose. A specification was produced by AgustaWestland and approaches made to a number of potential suppliers. The primary requirement was to be able to test a number of samples simultaneously in a dynamic environment allowing comparison of candidate materials against a known control sample.

5.2 Design of Dynamic Test Rig

Following a competitive tendering process a contract was placed with Vixen Surface Treatments Ltd. The test rig consists of a modified sand blasting cabinet with separate filtration to avoid issues associated with silicosis and a hopper providing a metered supply of erodent into the main chamber. Figure 9 shows the test rig installed in the materials laboratory at AgustaWestland's Yeovil facility. The erodent is supplied from the hopper via an adjustable feed valve onto a vibratory feeder and a split funnel before being introduced to the high velocity air flow via a venture nozzle arrangement. Upon entering the air stream the erodent is accelerated into the erosion chamber where it impinges with the specimen. Waste air and fine sand is vented whilst large particles drop out of suspension ensuring there is no possibility of air re-circulating. A novel feature of the test rig is the rotating sample carrier which can be seen in figure 10. This provides the capability to impinge the samples in a highly dynamic environment and provides the opportunity to test a number of samples simultaneously. The samples are 50mm x 50mm carbon fibre “stubs” approximately 2mm thick coated with standard blade paint on the test face. A range of candidate erosion protection materials (paints, coatings, tape, etc.) have been applied to these samples in preparation for testing. By use of a “standard” control sample with well understood performance characteristics it will be possible to conduct comparative tests against the candidate materials with a clear understanding of what will constitute a good result.

Figure 9: The blade erosion rig developed for this programme in situ in the materials laboratory at AgustaWestland, Yeovil. (image courtesy of AgustaWestland)

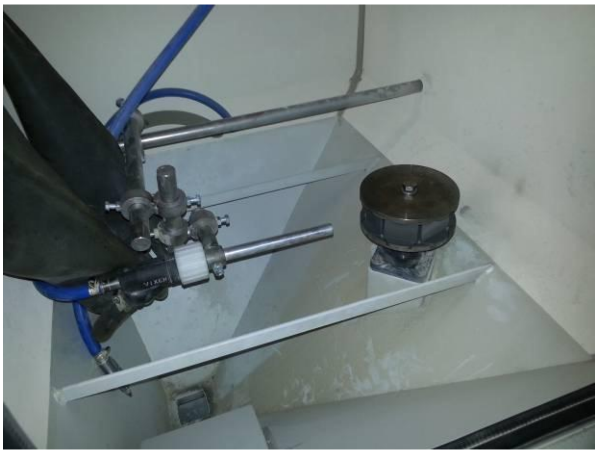

Figure 10: Internal view of Blade Erosion rig showing rotating sample carrier and ejector nozzle. (image courtesy of AgustaWestland)

At the time of writing the erosion rig had been commissioned and testing of candidate materials is expected to start shortly. Preliminary results of the analysis are expected by the end of the year.

6. NEXT STEPS

6.1 Testing

The dynamic test rig described in the previous section is expected to be in use by the time that this paper is presented. This will provide the opportunity to test candidate materials at a relatively low cost with the goal of determining a “best of breed” solution.

6.2 Collaboration

The authors are keen to invite interested parties to provide samples for evaluation using this facility. Materials that require little or no maintenance and provide a lightweight and low volume solution would be most welcome. The benefits to be gained from materials that provide a robust solution capable of operation in both rain and sand/dust environments are significant.

In addition we are keen to develop linkages with researchers outside the UK who are engaged with the search for a long term solution to the problem of blade erosion.

7. CONCLUSIONS

Military helicopters are increasingly being called upon to operate in conditions where they routinely land and take off in brownout conditions. The erosive properties of the sand and dust encountered can rapidly cause serious damage to main and tail rotor blades that lack some form of protection. An assessment has been undertaken of in service experience of damage caused to rotor blades by erosion from operations in this environment.

A study has been conducted to look at the options for providing protection to rotor blades from operation in these conditions; this concluded that at present blade tape that is maintained effectively provides the most cost effective solution.

In the longer term a number of new technologies have been identified that could provide a good solution requiring less maintenance than those currently available. A dynamic test facility has been developed to assess the performance of evolved versions of current materials and future developments.

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