

OLD AIRCRAFT, NEW FAILURES

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Abstract. Most of today's rotorcraft are designed with a service life of 20 years or more, with possible life extensions and mid-life upgrades to engines, airframes and equipment. During this time, the demands on the rotorcraft will change, and with each change in role a different set of variables will be introduced with regard to the life expectancy and performance of the platform as a whole, and on each of the individual components. Many items are monitored during the life of an active fleet of rotorcraft, with the fleet leaders being examined regularly in order to anticipate any issues the other aircraft may encounter. As an aircraft fleet nears the end of its service life, the fleet leaders are withdrawn from service and those airframes with the lowest number of flying/operating hours and in the best condition will be chosen to see the platform through to retirement and possibly further to historic display aircraft. However, it is during these last few years that new failures have been seen to occur.

This aim of this paper is to highlight the problems that can occur when a rotorcraft platform nears its retirement with the example of a failed tail rotor drive shaft coupling. Thus showing that whilst embracing the new, consideration should also be given to older materials and manufacturing processes that are still in use. It is here that examples of what may occur in the future to today's aircraft may be found. After all, today we are designing and building the historic rotorcraft for tomorrow.

INTRODUCTION

The Materials Integrity Group (MIG), which is within the Defence Equipment and Support (DE&S) organisation of the United Kingdom Ministry of Defence, can trace its history back to the end of the Second World War when there was a significant increase in the number operations of combat and support aircraft in a maritime environment [1]. Throughout these operations, a number of material problems were highlighted that had not been observed with land based operations. These included corrosion of the aircraft structures and fuel quality problems. Because of these issues, the then Director of Aircraft Maintenance and Repair decided that there was a need for a Fleet Air Arm (FAA) specific support organisation to investigate and advise on these problems. Thus a small laboratory was built at Fleetlands, Gosport in 1946 and was operated as an out station of the Admiralty Central Metallurgical Laboratory. During the first 8 years, differences became apparent between the activities of the parent organisation and the out station and as such the Laboratory at Fleetlands became the Naval Aircraft Materials Laboratory (NAML), a scientific department of the Naval Air Command.

Many of the initial tasks for NAML were likely to have primarily been for fixed wing aircraft due to the larger number of these aircraft types being flown by the FAA, but close ties were also formed with rotary wing aircraft. In 1944 the first Sikorsky R4 helicopters arrived in Britain for the Royal Navy [2] and were operated from HMS Daedalus (Lee-on-Solent) in 1945, where they were flown within a mixed fixed wing and rotary wing aircraft squadron [3]. Then in 1947 the first dedicated helicopter squadron was formed at HMS Siskin (Gosport) [3] and the 'Hoverfly' fleet was moved to within approximately 1 mile of the NAML buildings. Close connections were maintained between NAML and the expanding helicopter world of the late 1940s and early 1950s, with the introduction into service of the Dragonfly, Sikorsky S-55, the Whirlwind HAR.1s and the Hiller HT.1s. All of these aircraft were flown by the Royal Navy 705 Squadron from HMS Siskin [3] together with other dedicated helicopter squadrons.

Over the following years, NAML expanded in order to cater for the increasing needs and changing role of the Fleet Air Arm. During the 1960's and 70's this was to cater for the significant change from a fleet comprising of mostly fixed wing aircraft to one where the majority were rotary wing. At other times, expansion was necessary because of the development of technological systems to assist with monitoring of aircraft performance or the introduction of new materials.

In 2000, following the Defence Strategic Review, a major reorganisation of the support structure to all platforms within the Ministry of Defence occurred. This was to reflect the change in the operations of the Armed Forces and how best these operations could be supported. NAML did not escape these changes, it did change its name several times (with much humour at some of the abbreviated titles), but continued to grow becoming a Tri-Service organisation, covering all platforms (land, sea and air). The latest reorganisation of the support structure to the Armed Forces has led to the current MIG organisation, it is still Tri-Service but concentrates on support to the air environment platforms, and encompasses the elements on which the original Laboratory was formed.

During the 60 years of existence, MIG has seen a number of generations of rotorcraft that have been developed enter into to service, serve in various roles before passing into retirement, and for a few lucky aircraft, continue life as historical flying aircraft. At each stage of their life, MIG has and continues to support the helicopter platforms. And it is because of this unique background that personnel at MIG (particularly those within the Materials Assurance and Technology Division of the organisation) encounter new failures within components on older aircraft.

THE EVOLUTION OF THE HELICOPTER

Since the introduction of the earliest helicopters, many aspects of the design, build and maintenance of rotorcraft have evolved, some because of improvements in knowledge, materials, technology or regulations, whilst others have been due to operational requirements or financial pressure. All have been widely debated amongst the rotorcraft community. The reason for discussing the evolution of the helicopter here is that each 'generation' of helicopter presents itself with a unique set of variables. MIG supports aircraft from a number of the generations, vintage helicopters within military flying display teams and both new and older generation in service. Each generation imparts its own set of problems in terms of failure mechanisms and maintenance regimes.

The aircraft of the 1940s were designed and built within the 'Safe-life' philosophy [4]. Fatigue and S/N curves were being researched and were borne in mind whilst designing aircraft. It was considered that any fatigue failure events should be engineered so that they should be so far into the life of the aircraft, that during general service they should not occur [5]. In some respects this was achieved, but only because new found knowledge and developing technology meant that new and improved helicopters appeared at frequent time intervals. As such the helicopter models in service during the late 1940s and early 1950s only had an operational life of 2 – 5 years before becoming obsolete.

During this period, principles and arrangements were being created through the United Nations in order to preserve friendship and understanding among the peoples of the world with the advent of international air travel [6]. Regulations together with codes of practices were being developed in the US for airworthiness requirements for rotary wing aircraft [5]. Whilst back at home in the UK, discussions were being held on the best way to maintain helicopters with some clear divisions between those who preferred what might now be termed 'preventative maintenance' and those that would rather leave things that worked alone! [7] It was becoming clear by 1947 that helicopters were developing their own niche within the aircraft world and were being flown in challenging conditions even if it was occasionally just for publicity photographs [8].

During the late 1940s and early 1950s, it started to become apparent that not all fatigue related accidents had been avoided within the rotorcraft world [9], although these were not as widely reported as accidents within the fixed wing aircraft world, such as those of the Comet failures in 1954 [10]. These accidents lead to the evolution of the 'fail-safe' philosophy as an improvement to the 'safe-life' philosophy, and this was then introduced to the design and manufacture of aircraft during the 1950s and 60s [4, 9].

During the early 1950s, thoughts regarding airworthiness and its documentation were also evolving. During a meeting of the Helicopter Association of Great Britain in 1953 [11], references were made to using airworthiness documentation as a way for manufacturers to show potential purchasers the safety of their helicopters. And by 1959, when the American Federal Aviation Authority had taken over the duties of the American CAA, documentation had developed into aircraft type certification documentation [12].

As the 1960s neared, the in-service life expectancy of rotorcraft were beginning to be extended beyond the 5 year mark, some of which could be attributed to the cost of each of the platforms. Helicopters were being widely used all over the world in environments as diverse as the African bush and the Antarctic [13]. Thus improvements in knowledge and technology were being demanded in order to maintain fleets of aircraft in these environments, and it is in this light that crashworthiness programmes were implemented such as those of the US Army during 1959 [14] and aircraft teardowns began.

It is likely that as a result of aircraft teardown type activities that the 'damage tolerance' or 'safety by inspection' philosophy developed during the 1970s [4]. The information gained on the extent of corrosion in particular areas or locations of cracks that had been found during these exercises enabled the introduction of modifications to current aircraft and their maintenance procedures. In addition new aircraft were designed and built to extend in-service lives further towards the 20 year life mark. Full scale crash testing programmes were underway within the 1970s such as those of the US Army and Messerschmitt-Bölkow-Blohm [15, 16]. The development of the computer enabled the results of these tests to be

modelled with software such as the first version of the KRASH hybrid modelling programme [15, 16].

Although the news coverage of this time heavily portrayed helicopters within their military roles in Vietnam, other events were occurring of a less hostile nature. Within the UK, Bristow Helicopters performed their first civil rescue within 4 days of joining the coastguard service [17]. Boeing announced their intentions to build a new tilt rotor aircraft [18] and the first composite material parts were being made to be fitted to Bell Huey helicopters [19]. Much research was being undertaken around the world to understand more about the environments in which the aircraft were being operated and how if damage occurred it could be easily repaired. With the use of computers on the increase, there was also a world of possibilities as to what could be invented to assist the helicopter pilot and crew either in aircraft retrofits or in the new generation of helicopters.

The latest generation of aircraft can be seen to employ the latest in materials and design technology for building light weight structures with aerodynamic designs (e.g. composite materials) and more powerful engines. Safety can be seen to be a prime concern with the protection given to primary systems, the latest helicopter seats [20, 21] and various fire detection systems [22]. Crashworthiness of aircraft has become a hotly debated issue, with crumple or crush zone structures, such as those within the NH90 [23], being incorporated into many aircraft types to reduce the energy impact on a helicopters occupants in the event of an accident.

As before, the latest technological advancements are being utilised wherever possible within the rotorcraft world today. This can be seen within the helicopter cabins with the 'glass' cockpits, navigational instruments, flight aids and specific role equipment. Many systems health monitoring devices are being employed, which rely heavily on the latest technology available – a further evolution of the 'safety by inspection' philosophy and possibly in the future, a 'maintenance when required' philosophy. Advancements in technology are also being more heavily relied upon at the design and certification stages. Where once stress calculations of airframes were conducted by hand, computer modelling is now utilised and in a drive to reduce costs, computer simulations are being conducted to reduce the amount of coupon, component and whole aircraft testing required to meet the stricter airworthiness regulations of today.

All of these aspects have contributed to helicopters become more expensive to develop, build and maintain, and as such the latest generation of aircraft are to be expected to remain in service for much longer than their forebears, with some aircraft being expected to remain in service for nearly 50 years.

THE LIFE OF A HELICOPTER

At the beginning of the life of a helicopter, the testing and development work that has been conducted from the initial design concept stage through to full scale production, should help to minimise the number of failures that occur on or with the various components and equipment fitted. However it is recognised that some infantile failures will occur. Some failures may be due to incompatibilities with equipment or materials, previously unknown load paths or situations may be discovered that were not covered by pre-production testing or computer simulations, components may not have been made to the best design or with the correct materials, or manufacturing practices may require further refinement. Many of these

teething problems are ironed out as the helicopter platform matures and failure rates reduce. It has been noted that this phenomena is not confined to the rotorcraft industry and that occurs with virtually all products, resulting in the development of the first part of the ‘bath tub’ curve failure observation diagram, Figure 1 [4]. As aircraft reach the end of their lives, it is widely acknowledged that wear, fatigue and corrosion become more frequent failure events on airframes and components [24, 25], which can then be seen as the last part of the ‘bath tub’ curve in Figure 1. Some might say that the art of designing and/or owning a helicopter or fleet of rotorcraft is to keep the middle part of the curve as long, as low and as flat as possible, and preferably for the lowest outlay!

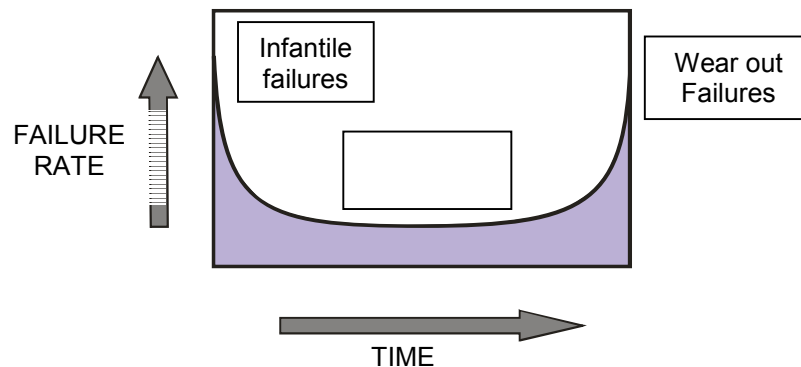


Figure 1: ‘Bath tub’ failure observation diagram.

The life of a rotorcraft can be defined in a number of ways [4, 26]. Firstly there is the chronological age of the aircraft i.e. the number of calendar years since it was built. Corrosion driven failure mechanisms of metallic materials are linked with this time scale. Then there is the usage time scale which is how far it has progressed towards the end of its design life. This would be based upon flight profiles, usage spectra and service utilisation [27, 28]. Wear and fatigue driven failure mechanisms are often prominent with this usage scale. The two age scales should be considered together when viewing the whole life of an aircraft as age related failure mechanisms can exacerbate usage driven ones [4].

Various methods of prolonging the life of rotorcraft, both in terms of chronological and usage ages, have evolved since the first production aircraft were built. Scheduled maintenance procedures have been introduced since the late 1970s [25] and it is now common practice to overhaul components at set flying/operating hour time markers, for example with engines and gearboxes, in order to replace parts that are known to wear or perish. ‘Service Bulletins’ are issued for inspection and/or repair and maintenance of components and airframes [29]. Corrosion prevention or protection procedures may be introduced and mid-life upgrade or life extension programmes may be developed [26], especially in light of information from aircraft teardown exercises and the experiences of the users. These life extension procedures can be particularly effective in situations where the flight profiles are well established and the full effects on the aircraft are known and understood. But care should always be exercised during any life extension programme to ensure that all of the relevant facts have been established. The first production helicopters were generally built for one specific role until the end of their useful life, while the helicopters of today are designed so that during the life of the aircraft they may be equipped for different tasks. These will invariably involve different flight profiles and usage spectra, and in order to extend the utilisation period of the airframe, trade-offs will be employed between the amount of high-time/low-stress low-time/high-stress operations for which the rotorcraft is employed as the design life is consumed.

As a fleet of aircraft near the end of their in-service life, reviews are made of how many aircraft are required to see the active fleet through to the end of its role. The numbers of aircraft are reduced, often by retiring the fleet leaders, these being the airframes with the highest number of flying/operating hours or are those closest to the end of their designed life (or extended design life). The spares held in storage to keep the last of the fleet airborne are often reduced both because of the need for space for other aircraft types and because the cost of replacement parts becomes beyond economical viability. As the fleet reaches its last one or two years of service, the rationalisation process may be repeated and serviceable parts may be salvaged from the retired aircraft just to ensure that the last aircraft can remain flying.

With historical flight aircraft further problems may also be encountered. These helicopters are often reduced to flying 50 - 60 hours per year and the rationalisation of spares is further repeated. The maintenance schedules of inspections every 300 hours (or more) that were applied whilst the aircraft was in service become nonsense as this would mean that they are only inspected once every 6 or more years. Therefore calendar back stops need to be introduced especially where degradable materials form part of the system.

NEW FAILURES ON OLD AIRCRAFT

During the latter stages of a helicopter's life new failures may be encountered and this is not only because people are always finding new ways to break things! It may take many years for design or manufacturing faults to occur under load as with Stress Corrosion Cracking (SCC) or hydrogen embrittlement.

The structures and components belonging to helicopters which have their roles changed at a mid-life point should be reviewed in their entirety to ensure that they are suitable for their next role. As previously stated, new roles inevitably mean different flight and loading profiles on the airframe and all of its component parts. Stress calculations need to be revisited in order to evaluate the new life expectancy of the aircraft fleet. But it has been found that not all computer based methods give the same results and that these may be different again to those produced by the hand calculated methods [30]. There may be incompatibilities between design philosophies for when the rotorcraft was initially designed and those of today. Using computer methods for re-examining old calculations can show that much more of the design life has been utilised with the design considerations of today than first expected. The data on which many life calculations may be based could be missing or flawed and data capturing problems have been reported for older aircraft [31]. The extent to which older aircraft have been pushed to their limits relied upon the conscience of the pilots, whereas modern systems health monitoring and flight data recording systems record what they monitor. The incompatibility of recording systems is also problematical, with data gathered on the computer technology systems of the 1970s not being easily read by the technology of the 2000s, and this is likely to be a recurring problem with today's technology not being able to be read or supported by tomorrow's.

Modifications to airframes to rectify known problematical areas of fatigue cracking, by 'beefing-up' the structure, have led to cracking occurring in unexpected areas that are often more difficult to inspect or repair than the initial problem area. Engine upgrades, where more powerful engines have been fitted may result in airframe cracking if suitable remedies are not taken. Upgrades to flight systems can also present problems. The introduction of systems that make a rotorcraft easier to fly, such as fly-by-wire systems, can result in pilots pushing aircraft to the extremes of flight envelopes more often [26] and thus initiating new failures.

Whilst examining a helicopter for life extension programmes, the whole platform is often divided into systems, i.e. engine, gearbox and airframe. However occasionally fittings and components are overlooked which link the systems together. Simple 'P' type clips that are not life limited, can fail due to fatigue where they are attached to fixed points on the airframe, but may subsequently result in wear, fretting or fatigue failures in wiring looms or fuel or hydraulic pipelines that they are securing.

Wiring looms may need to be replaced during the life of a helicopter. This is often a daunting process as each aircraft may hold more than 2 miles of cables, but connections between components and sections of looms may become corroded. Wire coatings can deteriorate due to the aging processes affecting the coating materials used or due fretting or wear between the wires in bundles. The loss of wire coatings can result in shorting of the electrical currents from within the wire to nearby metallic objects, causing faults on the main electrical equipment or more seriously, arcing which can ignite local flammable materials, examples of which have been investigated by MIG.

Helicopters that were initially intended to operate from land locked environments can be affected by a rash of new failures when put into a marine environment. Corrosion may become a significant problem for dry built airframes and components once free from SCC may find that they are now in an ideal environment for this failure mechanism to be prevalent. It is often not the clearly visible structural parts that are affected, but moisture and salt water have been known to infiltrate honeycomb structures [32] and electronic components like micro-switches as well as sit hidden within lightening wells and recesses of components.

Aircraft nearing end of service can often be affected by the accumulation of problems which have occurred over many years. The repeated removal of light corrosion by gentle abrasive techniques can result in the excessive thinning of material which may not be noted because it has not been conducted as one maintenance action [26]. Structural repairs requiring fastener holes to be re-drilled to oversize dimensions can result in insufficient edge material to carry the required load [26]. Bonded repairs can deteriorate due to degradation of the adhesives and combinations of repairs on the same component can reduce the load carrying capability of the structure.

The rationalisation process when applied to parts may also inadvertently introduce failures. To a layman, silver plated nuts and bolts may look similar to cadmium plated nuts and bolts. The manuals may say that the silver plated parts could be used in some areas where the cadmium ones are specified. However liquid metal embrittlement failures have been noted by MIG when cadmium plated parts have been used in hot engine environments where the silver parts were specified.

Occasionally new parts need to be sourced to keep the helicopter flying, possibly due to the rationalisation of stores being a bit too zealous, parts being stored inappropriately or due to an unexpected consumption rate of the held spares. The exact reasons why some parts were made in a particular way or why a particular material or lubricant was specified are often lost over extended periods of time, especially for those older aircraft that designed on paper alone. Thus parts are sometimes purchased, which although look the same shape as those fitted to aircraft may not be the same 'inside' and may fail because the new components are unable to carry the loads required, because the wrong temper material has been used or because the alternative lubrication cannot withstand the operational environment.

A CASE STUDY

This case study is an illustration of a failure that occurred to an older generation helicopter, one that had been designed during the 1950s and that was approaching its end of service life which was over 40 years. From this example it can be seen that a number of issues came together resulting in the failure.

The accident occurred shortly after take-off when the helicopter lost its yaw control and the initial on-site examination of the aircraft identified that there had been a failure of the forward flange assembly of shaft section 2. This flange assembly connected the Tail Rotor Drive Shaft (TRDS) section 1 from the Main Rotor Gearbox (MRGB) to the rotor brake on the TRDS section 2, Figure 2. Its roles in the system were to transmit drive via the TRDS to the intermediate gearbox and when rotor brake was applied, to carry the retardation loads from the brake to the MRGB.

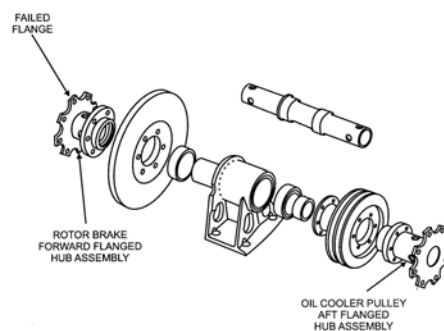


Figure 2: Schematic view of Shaft Section 2 showing assembly detail and location of the failed Hub.

The initial examination of the components revealed that the Forward Flanged Hub had failed through the flange wall thickness adjacent to the radius at the flange/hub change of section. The flange had remained attached to the aft face of the TRDS Section 1 whilst the body of the hub remained attached to the TRDS Section 2. The flange section of the Hub had failed into three distinct pieces, each of which remained bolted to the Shaft Section 1. None of these pieces exhibited any significant distortion or yielding apart from a small area of the flange adjacent to a missing bolt head (Figure 3). The painted surface of the flange had been scuffed, the locking tabs had been distorted and one of the bolts had failed however this damage was consistent with being struck by the other part of the hub during the accident. The hub portion was still securely attached to the Shaft Section 2, and other than the fracture no other damage or distortion of the item could be found. The fracture surface had been obliterated where it had impacted the other half of the assembly during the accident. It was noted that there were an abnormally large number of shims between the flange and the aft face of the TRDS Section 1. Coupled with the damage to the components, it was concluded that the Hub had been experiencing high axial stress loading prior to its failure.



Figure 3: Plan view showing the fractured flange still attached to Shaft Section

Once the parts had been dismantled, it was possible to see that the forward flange face was anodised and unpainted – as specified, with no significant damage to the anodised layer. A mottled appearance of the layer was noted but it was considered to be a result of the anodising process rather than of its deterioration in service. The examination of this surface under a magnification of X30, however revealed a high density of surface pitting.

The examination of the fracture surfaces on the flange section of the Hub showed that the fracture paths had generally followed the radius of the flange/hub change of section and their overall appearance indicated a slow growing failure mechanism with the cracks having been in existence for some time prior to final failure. Examination under magnification revealed that the fractures were associated with the pitting noted on the anodised face and that there was evidence of secondary cracking. Features also were identified which were consistent with multiple crack initiation sites around the radius of the flange/hub. Using a Scanning Electron Microscope (SEM), SCC was identified as the prominent crack propagation mechanism that originated at the pitting (Figure 4), with small areas of fatigue interspersed.

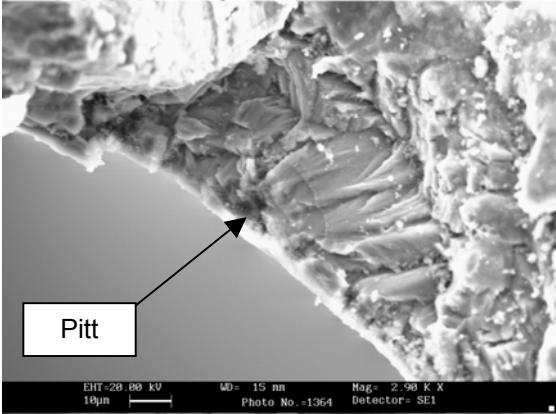


Figure 4: SEM view showing crack initiation and propagation from corrosion pit

Sections were taken through the hub and flange, polished and etched which revealed the forging structure and anodising. Thus revealing that the corrosion pits had been present before the final stages of manufacture, as the anodised layer was present within the corrosion pits (Figure 5). The etched microstructure also showed that the grain structure was highly orientated across the flange thickness at 45° from the vertical (left, Figure 6) and that the corrosion pitting was associated with the exposed end grain structure, as the deeper pits followed the same 45° path (right, Figure 6).

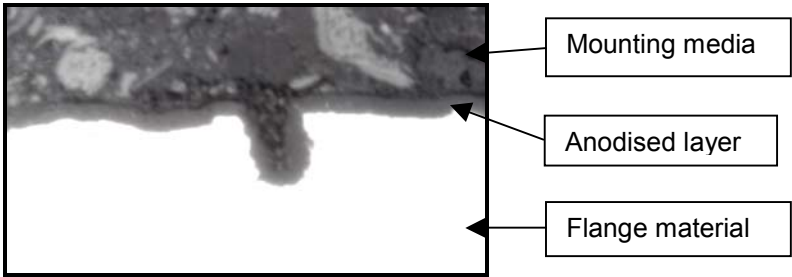


Figure 5: Micrograph showing the anodising layer inside one of the corrosion pits.

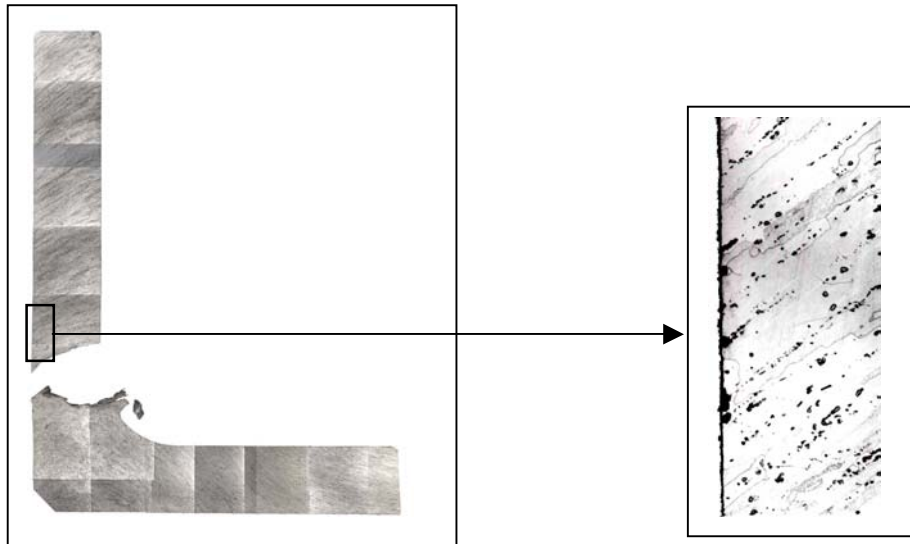


Figure 6: Micro-section of failed hub showing (on left) highly orientated grain structure from forging and (on right) corrosion pits orientated along grain structure.

Analysis of the Hub material confirmed that it was consistent with a 4% copper aluminium forging alloy and from conductivity measurements, it was found to be in the T6 condition – as specified on the component drawings. This alloy material was known to be susceptible to this failure mechanism when placed in a marine environment (the environment in which the aircraft was operating) with the component having residual stresses from both the manufacturing process and from its installed position. However it was not clear why this particular component should fail when compared to others which had been in service for much longer periods of both calendar years and flight hours. Interrogation of records held on failures of components for the helicopter type revealed that this particular component had never failed before or had ever been found cracked. Therefore as with similar types of investigations, the history of the flange assembly was researched. This revealed that the shaft assembly had been refurbished in 2000 and at this time a new Hub had been fitted. The Hub had been manufactured in 1996 and was from a batch of components that had been purchased in order that the aircraft could remain flying during the last years of its in-service life. From the aircraft's records, it was noted that it had only flown approximately 350 hours before the accident occurred.

Comparisons were then made to Hubs both from the same batch as the failed one and to those from other batches. It was found that other components from the same batch displayed similar pitting and grain structure orientation, thus it was likely that they would have a similar susceptibility to SCC. Hubs from the previous batches, were found to have some pitting but not to the same extent as the newer Hubs. The most marked difference was however the lack of the highly orientated grain structure that had been noted on the newer Hubs. It was discovered during the investigation that the machining of the forgings for the latest batch of hubs had been conducted off-axis, thus resulting in the highly orientated grain structure in the flange section of the hub that had significantly increased the components susceptibility to the SCC failure mechanism. The manufacturing faults had occurred because instructions on exactly how to machine the component had not been implicitly stated on the old hand produced part drawings and some of the technical expertise of forging master skills had deteriorated since the 1950s when the part was first manufactured.

It was determined that the flange had failed due to a combination of factors and that it would not have occurred if any of the individual factors were missing, these factors being the

susceptible alloy, the orientated grain structure, the pitting and the axial loading. Therefore if one or ideally more of the factors could be removed, then the rest of the helicopter fleet should not suffer a similar failure. It was not practical to change the component material to a more SCC resistant alloy as there was only a limited length of time for the fleet to remain in service. But it was possible to examine all of the aircraft within the fleet to ensure that the components were correctly shimmed, to establish that no other hubs had cracked and it was recommended that where possible hubs manufactured before the 1996 batch should be used.

IN SUMMARY

It can be seen that each generation of aircraft presents itself with a unique set of variables, with differences in design, build, maintenance regimes and life expectancy – both chronological and usage life. Types of failures to components/structures of older aircraft have been given with details of how changes in roles, operating environment, aircraft modifications or stores processes may introduce these failures. A case study has been presented where a new failure was found on an older aircraft because of the deterioration of manufacturing expertise over 50 years. It is possible that many of the failures presented here will be seen in the future on the latest generation of aircraft. Thus, in order to develop the more failure resilient aircraft for tomorrow we should draw on the experiences of the past.

REFERENCES

- [1] T. Wyatt, N. Jacobs, *“Performance Pays. Naval Aviation Fuels Monitoring”*, Journal of Naval Engineering, Vol. 40, No. 2, 2002, pp. 311-321.
- [2] ‘The Helicopter, History, Piloting and How it Flies’, J. Fay, 4th Edition.
- [3] Internet site, www.helis.com, data extracted 26 April 2007.
- [4] *‘How Old is Too Old? The impact of ageing aircraft on aviation safety’*, ATSB Transport Safety Report, Aviation Research and Analysis report B2005/0205, February 2007.
- [5] D.R. Garraway, *‘The Structural Airworthiness of Helicopters with Particular Reference to Fatigue Failures’*, The Journal of the Helicopter Association of Great Britain, Vol. 2, No. 2, 1948, pp. 18-24.
- [6] Convention on International Civil Aviation, also known as the *Chicago Convention*, 1944.
- [7] J Leason, *‘General Problems of Helicopter Maintenance’*, The Journal of the Helicopter Association of Great Britain, Vol. 4, No. 2, 1950, pp. 63-67. With details from the following discussion.
- [8] The Journal of the Helicopter Association of Great Britain, Vol. 1, No. 1, 1947.
- [9] P.F. Richards, *‘Continuing Structural airworthiness of civil transport aircraft’*, , Long-life Aircraft structures, The Royal Aeronautical Society 1980 Spring Convention, 14-15 May 1980.
- [10] Internet site, www.shippai.jst.go.jp/en, *‘Mid-air Explosion of Comet I over the Mediterranean Sea’*, Failure Knowledge Database, data extracted 2 May 2007.
- [11] H.E. Le Sueur, *‘Airworthiness of Helicopters and Lives’*, The Journal of The Helicopter Association of Great Britain, Vol. 6, No. 4, 1953, pp. 173-185.
- [12] World Helicopters, March 1959, Vol. 2, No. 2.
- [13] World Helicopters, January 1959, Vol. 2, No. 1.

- [14] H. Holland, K.F. Smith, *'Full Scale Helicopter Crash Testing'*, Energy Absorption of Aircraft Structures as an Aspect of Crashworthiness, AGARD Conference Proceedings No. 443, 1-6 May 1988, Luxembourg.
- [15] G. Wittlin, C. Caiafa, *'Transport Airplane Crash Simulation, Validation and Application to Crash Design Criteria'*, Energy Absorption of Aircraft Structures as an Aspect of Crashworthiness, AGARD Conference Proceedings No. 443, 1-6 May 1988, Luxembourg.
- [16] F. Och, *'Crashworthiness Activities on MBB Helicopters'*, Energy Absorption of Aircraft Structures as an Aspect of Crashworthiness, AGARD Conference Proceedings No. 443, 1-6 May 1988, Luxembourg.
- [17] Helicopter World, The International Rotorcraft Journal, Vol. 14, No. 6, June 1971.
- [18] Helicopter World, The International Rotorcraft Journal, Vol. 14, No. 8, August 1971.
- [19] Helicopter World, The International Rotorcraft Journal, Vol. 14, No. 11, November 1971.
- [20] Internet site, www.armorholdings.com, data extracted 10 May 2007.
- [21] Internet site, www.martin-baker.com, data extracted 10 May 2007.
- [22] O. Pastore, *'NH90 Helicopter New Fire Detection System for Engine and Main Gearbox Compartment'*, 28th European Rotorcraft Forum, 17-20 September 2002, Bristol.
- [23] D. Müller, R. Oster, J.-P. Scheitle, *'Analysis and Full-scale Crash Test of the NH90 Transport Helicopter Fuselage'*, 29th European Rotorcraft Forum, 16-18 September 2003, Friedrichshafen.
- [24] J.L. Rudd, *'USAF Aging Aircraft Program'*, Aging Combat Aircraft Fleets – Long Term Applications, AGARD Lecture Series 206, 1996.
- [25] A.F. Barnes, R.G. Mitchell, *'Living with the Ageing Structure'*, Long-life Aircraft Structures, The Royal Aeronautical Society 1980 Spring Convention, 14-15 May 1980.
- [26] D.L. Simpson, *'Canadian CF-18 Structural Life Management Program'*, Aging Combat Aircraft Fleets – Long Term Applications, AGARD Lecture Series 206, 1996.
- [27] P.R. Abelkis, M.B. Harmon, D.S. Warren, *'Continuing Structural Integrity Program for Transport Aircraft'*, Durability and Damage Tolerance in Aircraft Design, The Proceedings of the 13th Symposium of the International Committee on Aeronautical Fatigue, 22-24 May 1985, Pisa, Italy, pp. 395-422.
- [28] H.A. Wood, *'History of Loading of Aircraft and Examples of Aircraft Failure. Spectrum of loading'*, AGARDograph No 176, Fracture Mechanics of Aircraft Structures, pp. 3-7.
- [29] B.Hunter, *'Routine Maintenance of High Life Structures'*, Long-life Aircraft Structures, The Royal Aeronautical Society 1980 Spring Convention, 14-15 May 1980.
- [30] D.C. Borgman, D.P. Schrage, *'Synopsis of Specialists' Meeting On Helicopter Fatigue Methodology'*, Helicopter Fatigue Life Assessment, AGARD Conference Proceedings No 297, 14-19 September 1980, France.
- [31] P.E. Davidson, *'Coral Reach, USAF KC-135 Aging Aircraft Program'*, Aging combat aircraft fleets – Long Term Applications, AGARD Lecture Series 206, 1996.
- [32] *'Report on the Accident to British Aircraft Corporation/SNIAS Concorde 102, G-BOAB, over the North Atlantic, on 21 March 1992'*, Air Accident Investigation Branch, The Department of Transport (UK).