

ALUMINIUM ALLOY MMC 2009 - 15% SiCP

HIGH FATIGUE PERFORMANCES ALUMINIUM ALLOY FOR HELICOPTERS APPLICATION

Emmanuel LAILLET, emmanuel.laillet@airbus.com
AIRBUS HELICOPTERS Marignane, FRANCE

Abstract

In aeronautical field, material selection is the result of regular trade-offs between different criterions that may be conflicting: weight, cost, strength performance, susceptibility to flaws, reparability,...

The importance of these criterions will obviously change depending on the application (component) targeted, keeping in mind that light weighted structures remain a basic criterion for flying products. In order to minimize the weight while improving strength characteristics, AIRBUS Helicopters has developed for many years with its suppliers a metallic matrix composite, a 2xxx Aluminum alloy reinforced with 15% Silicium carbide particles, and proposes today many certified components manufactured with this material, on the full range of helicopters.

For decades now, AIRBUS Helicopters has gathered a huge manufacturing and in-service experience, showing the relevance of this very specific and particular material for the retained applications, and confirming the pertinence of the choice.

1. STRENGTH REQUIREMENTS FOR ROTORCRAFTS

Any rotorcraft component should be properly substantiated against applicable regulation, basically CS27/CS29 in Europe. Requirements are implemented in the EASA regulation, in terms of structural strength and more precisely through static requirements under limit and ultimate loads (CS27/CS29 §301, §303, §305) and fatigue / damage tolerance requirements (CS27/CS29 §571, §573).

On the rotorcrafts, the sizing of some components is mainly driven by static mode, the fatigue strength evaluation being only a consequence of the initial critical static sizing. In that case, the static performance of the material (Yield strength, ultimate strength) will be key in the substantiation loop, and on the contrary its fatigue performances will be of less importance.

For some other (metallic) components, which is basically the case for most of the rotor components, the fatigue mode is far the most critical one compared to static mode. In that case, the endurance limit of the material will be key for a proper sizing, and its static characteristics will be of less importance.

2. FATIGUE DOMAIN, COMPONENTS SUBJECTED TO FATIGUE LOADING

Especially on rotorcrafts products, helicopter

components may be subjected to many various types of loading, in terms of nature (acceleration, load, bending moment), amplitude and frequency (from static to 100Hz, even more). Material choices are consequently linked to the loading nature, its amplitude and frequency, and driven by their capacity to sustain static loads (Yield strength and Ultimate strength) or fatigue loads (endurance limit), or a combination thereof, with respect to their density and cost to manufacture and maintain. In other words, if a component is mainly loaded by static loads, the designer should prioritize high static characteristics (Yield and Ultimate strength), while if a component is mainly loaded by fatigue mode, especially under a high number of cycles, the designer should prioritize a high endurance limit at infinite cycles (Figure 1).

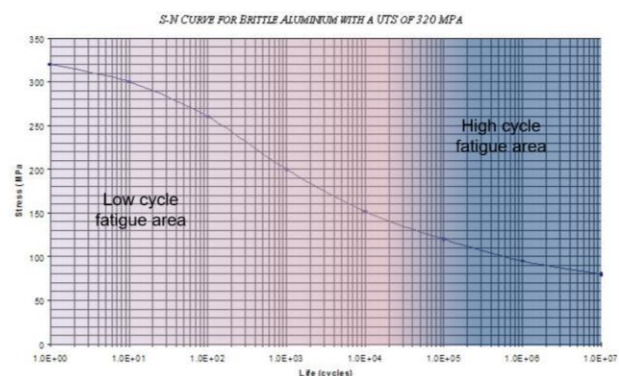


Figure 1 - Typical SN curve shape

Looking at conventional helicopters dynamic systems components, the replacement times are generally high (> 10 000 FH) in order to reduce Direct Maintenance Costs.

Taking into account the rotor rotational speed and a loading frequency of 1/rev at least, the cycles that the component will support in high cycle fatigue (HCF) during its operational life can be much higher than 10^8 cycles on a main rotor. On a tail rotor, whose rotational speed is even significantly higher, the number of cycles that can be applied frequently exceeds 10^9 , even 10^{10} cycles in its operational life. Many components, especially among the ones that are rotating on the rotors, are sized under high cycle fatigue mode.

Some components may also be mostly subjected to low cycle fatigue mode (LCF) and/or Ground-Air-Ground cycles, such as rotor start-stop cycles (typically about 5 cycles / flight hour, i.e. $< 5 \cdot 10^4$ cycles) or torque cycles (up to 40 to 50 torque cycles / flight hour punctually, for external sling operation, i.e. $< 5 \cdot 10^5$ cycles).

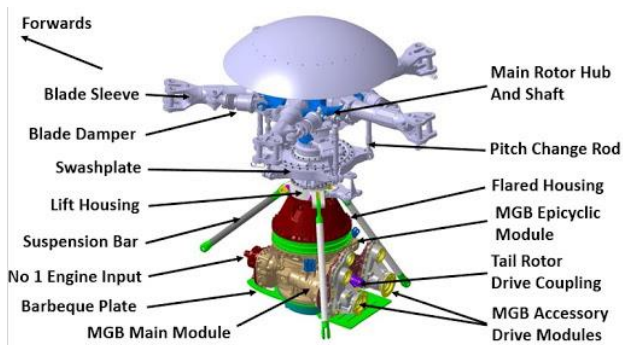


Figure 2 – EC225 Main Rotor

The third type of components may support both high cycle fatigue and low cycle fatigue loads in the same or different areas (the EC175 sleeve is in that case, as illustrated through figure 3). In this case, the material selection is more complex and will be even more dependent on the critical areas, specificities & technology of the dynamic systems as well as any development & certification constraints. For instance, if the service life limit of the component is strongly driven by an area subjected to high cycle fatigue loads, choosing a material relevant for high cycle fatigue may be more suitable than choosing a material having improved static or low cycle fatigue capabilities.

The following list provides the typical components and associated main loadings (that may strongly differ from one architecture to another one), based on the EC225 case of Figure 2 :

| Component | Main fatigue mode | Main loading type |
|-------------------------|-------------------|--|
| Blade damper | HCF | Lead-lag damper load and motions |
| Rotating swashplate | HCF | Pitch control rod load, rotating scissor load |
| Pitch change rod | HCF | Pitch control rod load |
| Lift housing | HCF & LCF | Non rotating scissor load, Suspension bar load |
| Suspension bar | LCF | Suspension bar load |
| Blade sleeve | HCF & LCF | Centrifugal load, Blade flapping moment, Blade lead-lag moment, Pitch control rod load, Lead-lag damper load |
| MR hub & mast | HCF & LCF | Centrifugal load, MR torque, MR lift load, MR mast moment |
| Non rotating swashplate | HCF & LCF | Non rotating scissor load, actuators loads |
| Barbeque plate | LCF | MR torque, upperdeck shear loads |
| ... | ... | ... |

Table 1 –Main components, fatigue modes and loading types

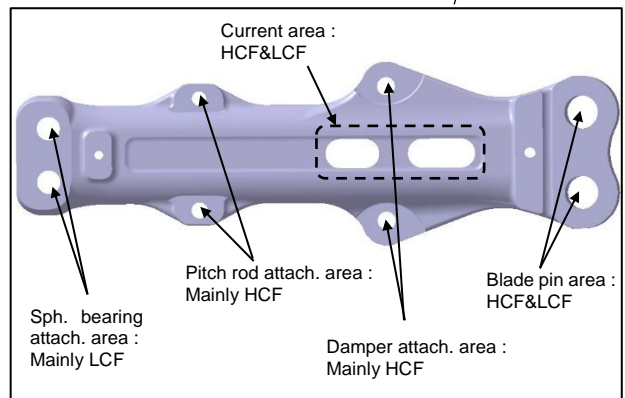
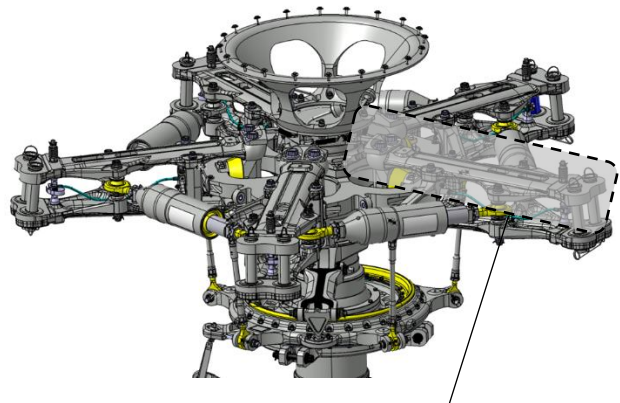


Figure 3 – EC175 Main Rotor sleeves

3. MATERIALS BEHAVIORS AND CHARACTERISTICS

3.1. General trade-off

Materials are generally chosen from multiple criterion such as static strength, fatigue strength (with and without contact), damage tolerance, stiffness requirement, weight target, costs target (to manufacture and repair), technical maturity, space allocation constraints,... and should also be chosen with respect to specific program contexts.

Nevertheless, it may be not sufficiently relevant nor meaningful to select any material based on one single criteria considered independently, as on the table 2.

| Material nature | Fatigue strength (w/o contact) | Weight | Cost |
|-----------------|--------------------------------|--------|------|
| Steel | 😊 | 😡 | 😊 |
| Titanium | 😊 | 😐 | 😐 |
| Alum. alloy | 😐 | 😊 | 😊 |
| Magnesium | 😡 | 😊 | 😊 |
| MMC 2009 | 😊 | 😊 | 😐 |

Table 2 –Trade-off on common materials

Other perspectives can be drawn, mixing together the criterion presented above :

- “Yield strength vs fatigue limit (with surface treatment)” – Figure 4.

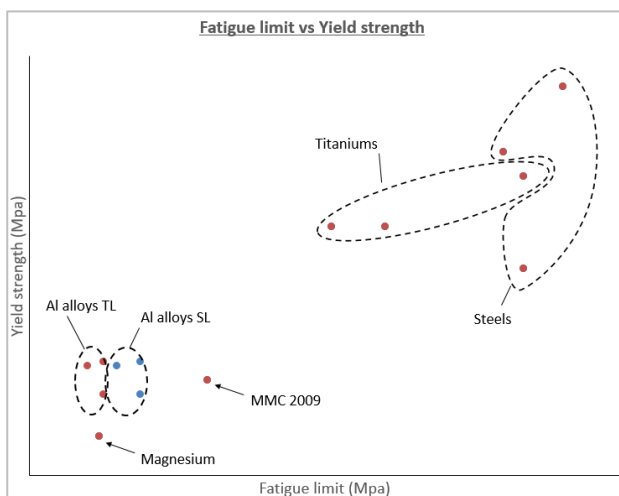


Figure 4 – Yield strength vs fatigue limit on several materials

- “SFP - Specific fatigue performance (with surface treatment) vs Yield strength” of these different materials – Figure 5.

$$\text{Specific fatigue performance SFP} = \frac{\text{Mean fatigue limit}}{\text{Density}}$$

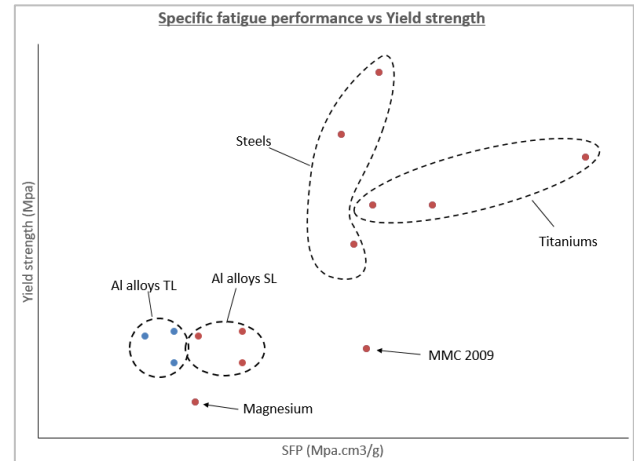


Figure 5 – Yield strength vs SFP on several materials

From this perspective, a material appears as very specific and particular. The specificity of the MMC becomes obvious, and this material appear as efficient as the Titanium, even Steel, for fatigue applications, especially when low cycle fatigue mode is not the most critical one, and even more when static strength is not a critical issue, which is the case on most of the rotor components.

3.2. Particular case : Fretting phenomenon

It is commonly agreed in mechanical field that any parts in contact may be subjected to “fretting-wear” (so called “wear”) or fretting-fatigue (so called “fretting”) or a mix of, depending on relative alternate movements and contact pressure between parts, unless specific mean is implemented to prevent from this phenomenon (see fretting wear diagram, figure 7).

Wear is associated to a progressive material removal at the interface leading to a progressive working section reduction. Fretting is rather associated to a degradation of one of the 2 parts in contact (basically characterized by dark degraded surface, as on figure 6), that typically evolve towards a fatigue crack initiation (figure 8), then the complete structural failure of one of the parts.

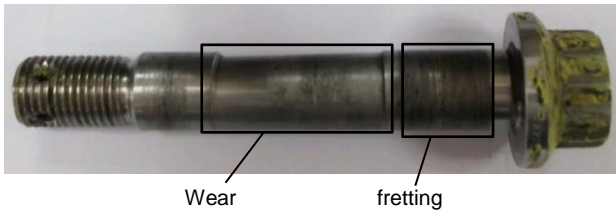


Figure 6 – Wear and fretting occurrence on a bolt

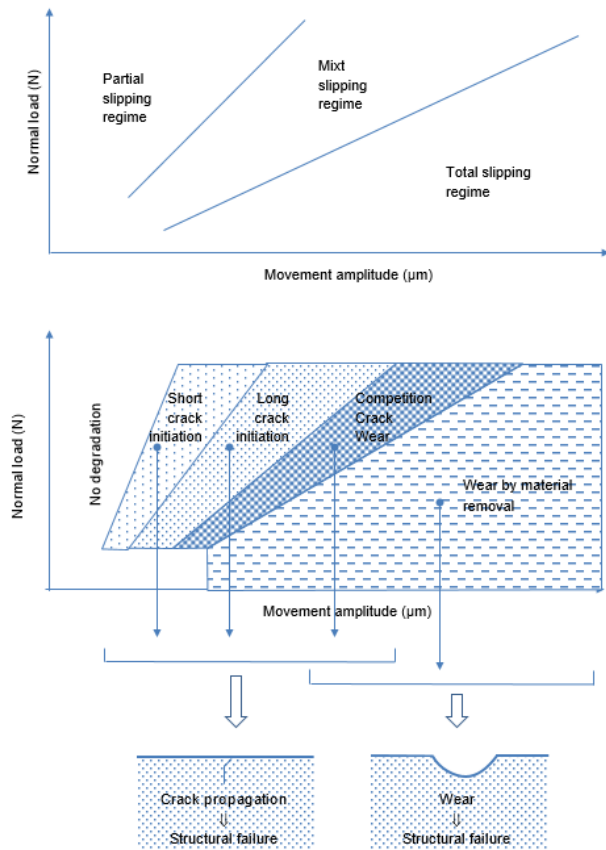


Figure 7 – Wear-fretting diagram, translated from Ref [10]

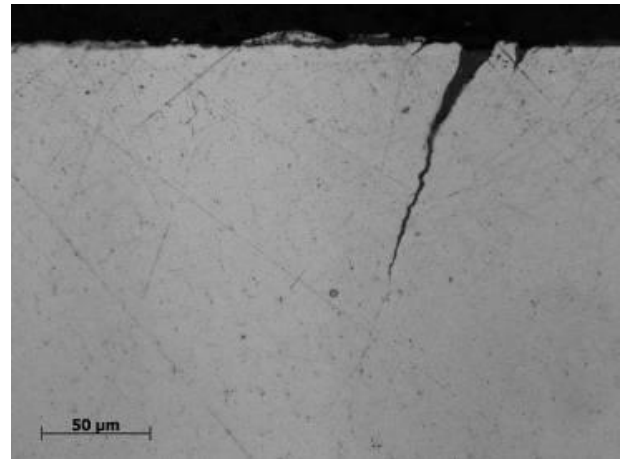
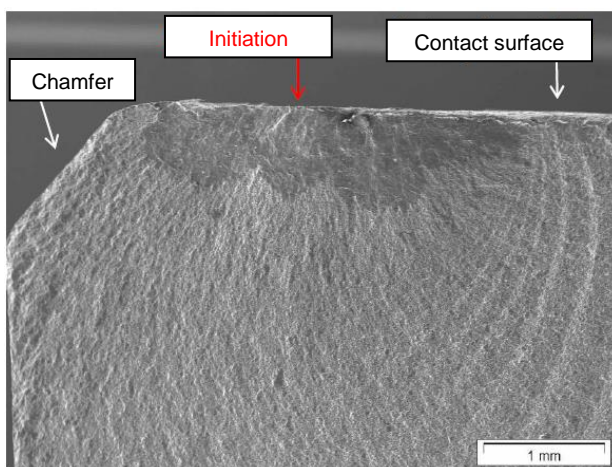


Figure 8 – 2 examples of crack initiations in fretting conditions

Different approaches may be retained by the industrials to account for both wear and fretting phenomenon.

Focusing on fretting that is generally more dangerous for strength since a crack initiation on a rotor part may lead very quickly to its complete structural failure (sometimes within very few flight hours), the degradation in service can appear for many reasons, depending on the design and tolerances of the parts, the assembly conditions (tightening conditions), the external environment (such as temperature and usage of the helicopter). It may not occur on some helicopters while on other ones, the same part or link will be subjected to fretting.

It is the reason why AIRBUS Helicopters chose for all materials used, years ago, the basic policy to consider that fretting was a permanent threat and was substantiated in fatigue accordingly, by ensuring for instance that fretting was properly developed during the full scale fatigue test. Another policy could have been to consider the fretting as an accidental remote threat only, but AIBUS Helicopters did not consider this approach as sufficiently reliable and safe.

3.3. Effect of grain flow direction on fatigue strength of conventional Al alloy

The fatigue strength of the materials may also be affected by the raw material elaboration process, thermal treatment and surface treatment. For example, an Aluminium alloy is significantly affected by the grain flow direction (see Figure 9, from Ref [1]) and its fatigue characteristics drastically reduce in the transverse direction (Figure 10). Coupon test results on classical Al alloys used within AIRBUS Helicopters have shown a strength

reduction of about -40% on endurance limit, in transverse direction compared to longitudinal direction (see Figure 10).

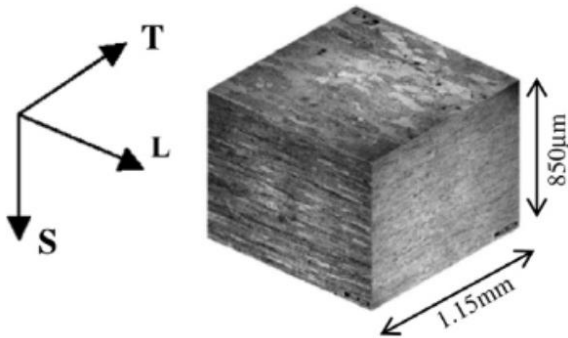


Figure 9 – Illustration of grain flow direction on 7010-T74511

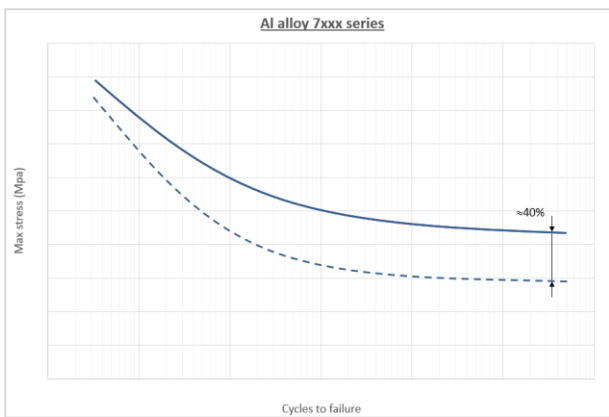


Figure 10 – Grain flow influence on Al alloy 7175 – Kt=1.035, R-1

3.4. Effect of pickling and anodizing on fatigue strength of conventional Al alloy

A conventional Aluminium alloy is also significantly affected by the surface treatment (pickling + anodizing) necessary to protect the raw material from the corrosion threat in service. The surface treatment process lead to an alteration of the surface quality, as illustrated in Figure 11 (from Ref [2]).

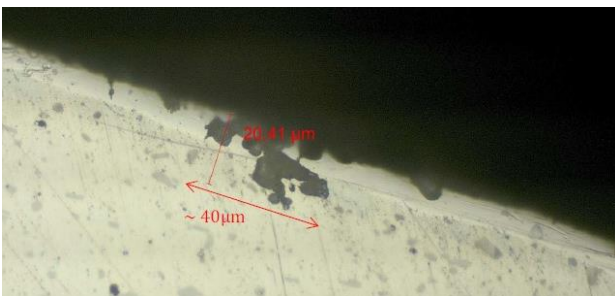


Figure 11 – Surface alteration resulting from pickling and anodizing

The Figure 12 also from Ref [2] illustrates the influence on fatigue life of the surface treatment (CAA) that can reach in this case -45%, based on coupon tests.

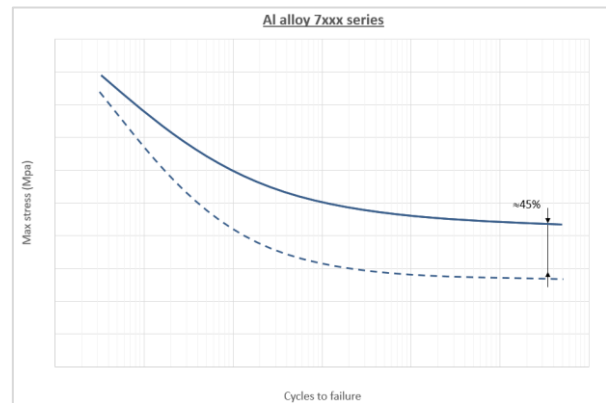


Figure 12 – Surface treatment influence on Al alloy 7050 specimen – Kt=1.035, R-1

3.5. Metal Matrix Composite 2009 – 15% SiCp

The MMC material is a derivative from the Aluminium alloy 2009, that has been reinforced with 15% of Silicium Carbide particles, in order to improve several characteristics, for applications such as ground transport, aerospace, thermal management, infrastructure,...

MMC material brings high thermal and electrical conductivity, high resistance to wear, low thermal expansion coefficient (CTE). But for sure, the strong interest of such material in helicopter structural applications rather lies in the strongly improved fatigue performances without contact, but also with contact (fretting conditions), compared to conventional Al alloy.

The material elaboration process ensure an homogeneous distribution, regular size of the SiCP particles within the material, without particles aggregation, (see Figure 13), ensuring a clear reduction of the :

- Sensitivity of the grain flow direction to the endurance limit at initiation (Figure 14).
- Sensitivity of the CAA effect to the endurance limit at initiation (Figure 15).

Indeed, as for most of the conventional Aluminium alloys, the MMC should be protected against corrosion, thanks to the application of a surface treatment, basically CAA.

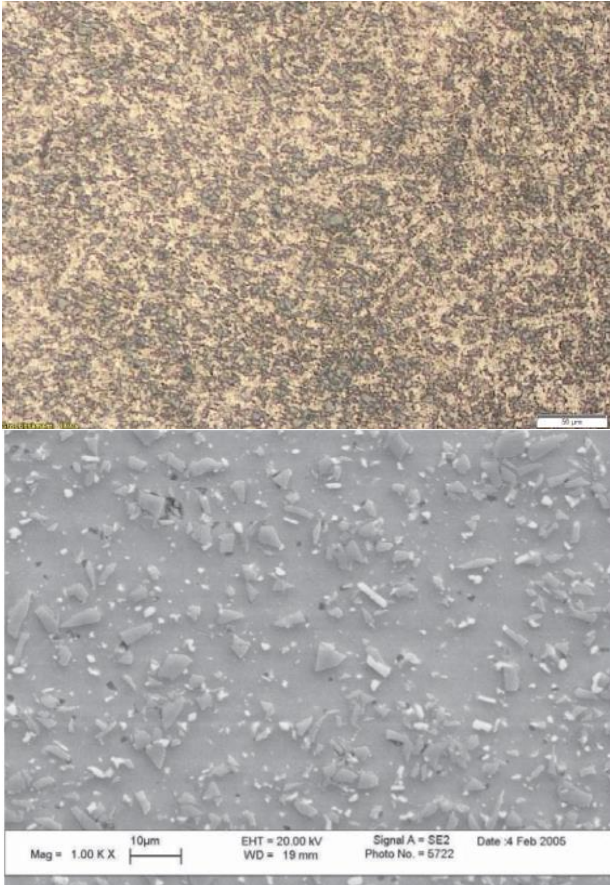


Figure 13 – MMC micrographic structures

Many type of tests have been performed by AIRBUS Helicopters, demonstrating the relevant fatigue performance of the material and its strong benefit compared to conventional Al alloy :

- With or without contact (fretting)
- With or without Stress concentration factor
- At different R ratio, allowing to characterize the Haigh's diagram ($R=-1$, $R=0.1$,...)

The following pictures illustrate the reduced effect of grain flow direction and surface treatment on MMC, compared to conventional Al alloy (respectively -10% and -15%).

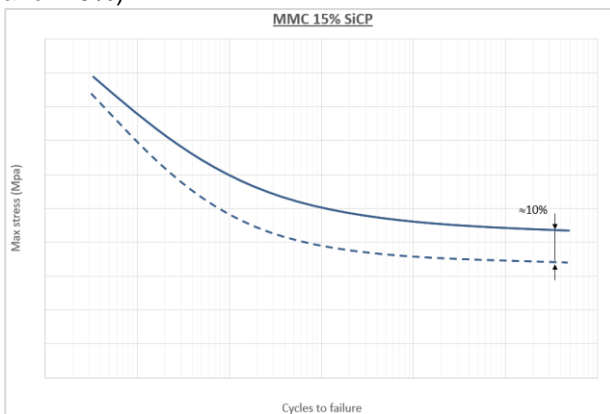


Figure 14 – Grain flow influence on MMC 2009 15% SiCP – $K_t=1.035$, $R=1$

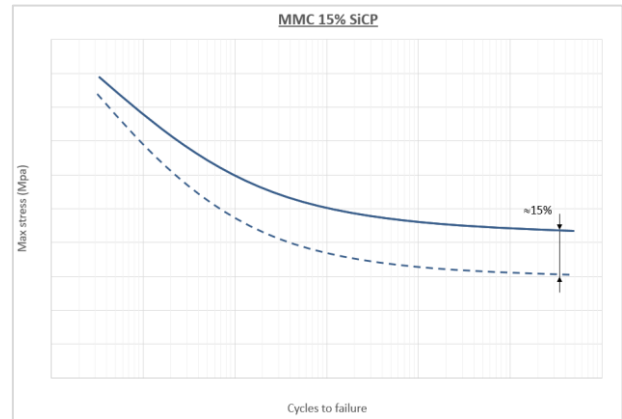


Figure 15 – Surface treatment influence on MMC 2009 15% SiCP – $K_t=1.035$, $R=1$

4. MMC APPLICATIONS ON HELICOPTERS COMPONENTS

4.1. Overall rotor applications

As introduced in chapter 2, thanks to the strongly improved high cycle fatigue behavior, MMC is used on several components that are mostly subjected to HCF, typically control chain components (fixed and rotating swashplates, scissors attachments,...), even sleeves, on several aircrafts such as EC120, EC155, EC175, EC225, H160,... All these MMC components are involved in functions whose loss/failure is CATASTROPHIC for the flight safety and consequently require the highest level of quality and constant performance.

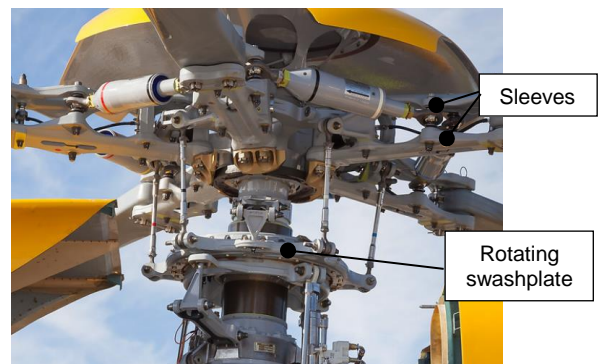


Figure 16 – EC175 main rotor with MMC components



Figure 17 –Main rotor sleeve in MMC

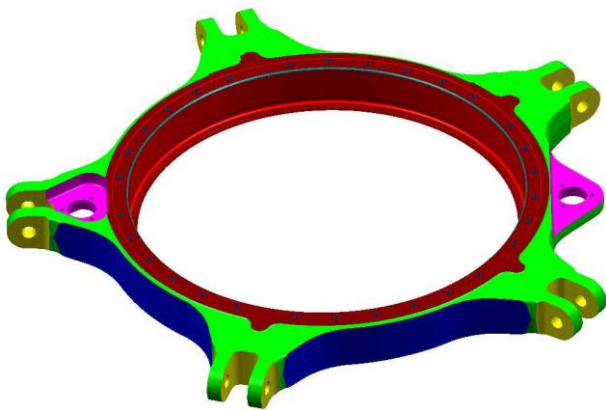


Figure 18 –Rotating swashplate in MMC

On the complete range of AH, more than 10 major components (references) are manufactured with MMC material.

4.2. Example of materials comparative analysis – trade-off

Several trade-off analysis have been conducted to choose the relevant materials, focusing on the impact on weight and costs, but also considering other requirements such as manufacturing constraints or stiffness needs.

For instance, the following trade-off have been performed in order to select the rotating swashplate material of the H160, whose design should be also driven from a stiffness point of view for a proper ball bearing behavior.

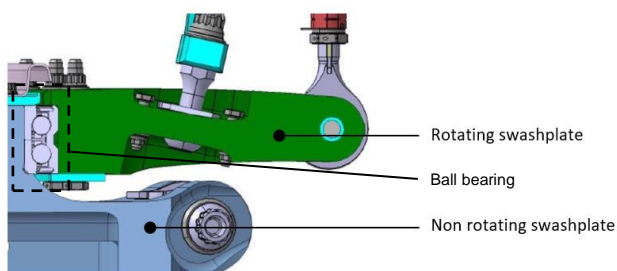


Figure 19 – Rotating swashplates section cut

Indeed, it should be ensured that the swashplate deformation under the dynamic pitch rod loads should not lead to detrimental peak contact pressures at the ball bearing level (Figure 19), potentially affecting its expected reliability. In this target, the MMC material also bring advantage in terms of increased stiffness (see Figure 20, from Ref [3]) that, combined with an appropriate design, is beneficial to properly transfer the loads and

deformations from the rotating swashplate to the non-rotating swashplate.

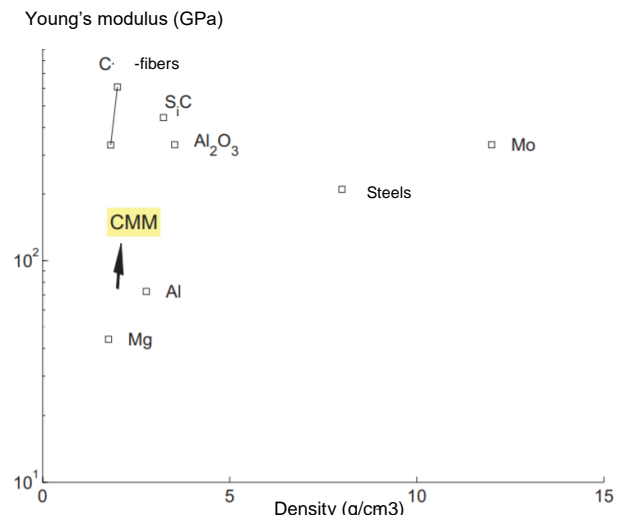


Figure 20 – Evolution of the Young's modulus with density, by reinforcements application



Figure 21 – Material trade-off for swashplate

The optimal retained compromise was to select the MMC material (Figure 21) as a basis for the rotating swashplate, thanks to its stiffness advantage and the strong weight benefit compared to Al alloy or Titanium (respectively +3.5kg, +5.5kg).

Another interest of MMC can be identified in order to help in the compliance to CS29§683 requirement that states : *"It must be shown by operation tests that, ..., the system is free from:*

- (a) ...;
- (b) ...
- (c) *Excessive deflection"*.

Indeed, MMC can improve the stiffness of the control chain by its increased Young's modulus, in minimizing, even suppressing the weight impact of the modification.

5. IN-SERVICE EXPERIENCE

5.1. Overall fleet

AIRBUS HELICOPTERS initially developed the MMC for EC120 certification in the 1990s, then spread it to many other products designed to operate in very various conditions :

- Operating location : all over the world
- Mission profiles : offshore operation, VIP, military operation,...
- Extreme environmental conditions : Outside air temperature from -40°C to +50°C, corrosive/marine atmosphere, icing conditions,...

The number of operating aircrafts flying with MMC components have accumulated several millions of flight hours (Figures 22 & 23). For sure, as for all products in such conditions, components are subjected to degradations (wear, corrosion, impacts, dents, scratches,...) but no specific nor severe issues have been highlighted up to now, related to the nature and/or behavior of the material (see also §5.2).

On the contrary, the volume of flight hours accumulated was the opportunity to demonstrate that the threats potentially affecting the parts were not different from other conventional Al alloys.

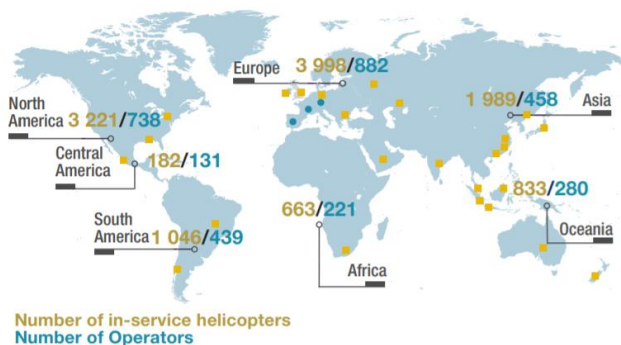


Figure 22 – Geographical distribution

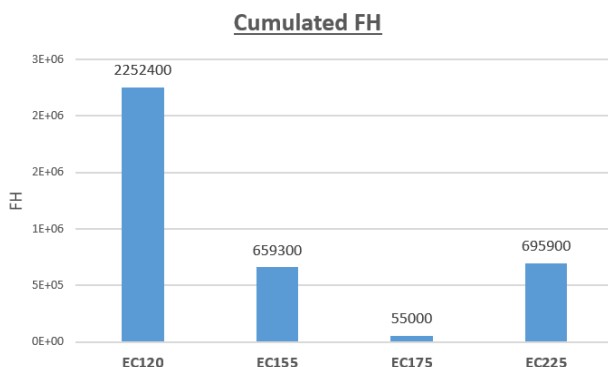


Figure 23 – FH of helicopters with MMC parts (2019)

5.2. Retex on MMC parts

Any anomaly from in-service experience, whatever the consequences in terms of safety, lead to the issuance of an event report within AIRBUS Helicopters : unexpected wear, accidental damage, problems during assembly or disassembly, clearance inspections, These anomalies can be detected either by the customer, the repair center, or AIRBUS Helicopters directly, during a scheduled or un-scheduled maintenance operation.

Any of these event reports lead to a preliminary analysis for safety classification, then implementation of protective and corrective measures if needed.

This process ensures collecting any noticeable in-service issue on the helicopter.

On the complete amount of MMC parts that are flying and the cumulated flight time (more than 3 millions FH), very few in-service cases of “youth problems” have been declared (about 2 issues per million FH on helicopters having MMC components), in saline atmosphere only, mostly due to inappropriate protection on bushes mounted on MMC parts, against galvanic corrosion.

It is to be noted nevertheless that galvanic corrosion issues are not specific to MMC, but are potentially affecting any Al alloy component in the same way. Other issues of galvanic corrosion are also raised on conventional Al alloys.

6. COSTS / MANUFACTURING ASPECTS

Costs for developing, manufacturing and maintaining in service some helicopters components are frequently expensive, especially when dealing with CRITICAL parts whose performance should be constantly monitored and ensured all along their life, from production to the removal from service, to conform with applicable regulation :

- Development costs (Non-Recurring Costs) are not significantly affected when choosing MMC. Indeed, on production side, specific more expensive tools should be used for machining, but less subjected to wear as contrary as other conventional cutting tools. On design office side, Non-Recurring Costs are strictly identical and could be even reduced thanks to the knowledge of the material, its poor sensitivity to grain flow direction, surface treatment and low scatter factor on endurance limit, letting the opportunity to reduce the number of tests to be performed for material/component qualification.

- Manufacturing costs (Recurring Costs) are driven by the cost of the raw material + machining + protection + assembly. The raw material price is the key driver for recurring cost determination. MMC raw material is for sure more expensive than conventional Al alloy. Particularly when static requirements are not the key driver for components sizing (high cycle fatigue mode being more important), MMC is a very efficient alternative to Titanium in terms of weight with, in addition, a less sensitive impact of manufacturing process on the fatigue performances of the component.

The machining costs of MMC is slightly higher than conventional Al alloy, mainly due to the need of Diamond cutting tools that are more expensive and the smaller thickness of every cutting pass. Nevertheless, as the Diamond cutting tools have a higher life limit compared to the Carbide cutting tools, the difference has not been shown to be significant.

The protection phase is dedicated to minimize the atmospheric corrosion threat (basically with CAA surface treatment) and galvanic corrosion threat by choosing proper materials galvanic couplings. Costs engaged to protect MMC or conventional Al alloy components are strictly identical.

Finally, the assembly phases (bushes, sub-systems) are not changed when using MMC compared to conventional Al alloy, the cost is consequently neither changed.
- No specificity is shown on MMC components in the in-service maintenance of helicopters : scheduled and unscheduled maintenance and removal criteria are identical between conventional Al alloys and MMC material.

7. CONCLUSION

The MMC 2009 -15% SiCP is now used for many years within AIRBUS Helicopters. Even if this new material is expensive, it brings many advantages, from a high thermal and electrical conductivity, to a low thermal expansion coefficient, a high resistance to wear and an increased stiffness compared to Al alloys. But the key advantage lies in the strongly improved fatigue performances that are key on helicopter components. Endurance limit is 2 to 3 times higher than on conventional Al alloys without fretting, 2 times higher with fretting, for a density equivalent to a conventional Al alloy. As shown in this paper, this step forward allow high weight savings. Out of these advantages “on the paper”, the best proof of efficiency is shown through the in-service experience. Only very remote incidents (few maturity

issues related to corrosion) have raised over the 25 past years, exactly as any conventional Al alloy. The maturity reached today on this material allow AIRBUS Helicopters to have strong confidence on it, for its development and extension on any appropriate component.

8. PERSPECTIVES

8.1. Shot peening on MMC parts

Even if it was shown that MMC brought many advantages in terms of fatigue behavior (with / without contact), improvements can also be investigated in order to improve again its fatigue strength, especially under fretting conditions. Indeed, the application of shot peening on Steel and Titanium materials is shown to be efficient to minimize the effect of the residual stresses due to machining phases, but also to delay the crack propagation linked to the fretting phenomenon (see example on figure 8), by the application of increased compressive stresses on the surface (figure 24, 25).

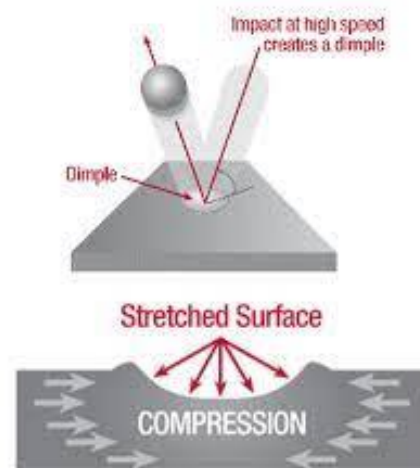


Figure 24 – Shot peening principle

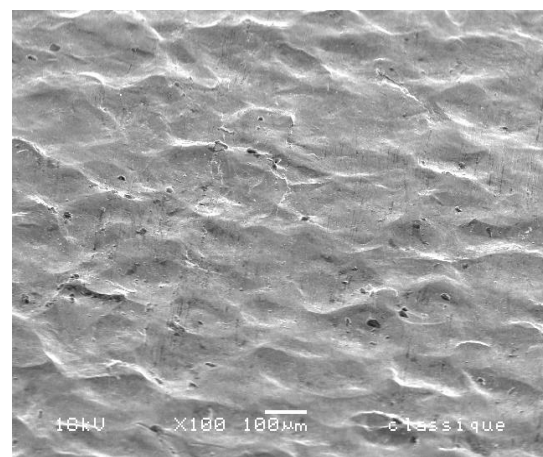


Figure 25 – Component surface after shot peening

8.2. Static strength improvement of MMC

It is shown on figure 4 that static strength of MMC may be higher than some Al alloys, and lower than other ones. To improve the interest of MMC for components that are more subjected to low cycle fatigue and/or the ones that are mostly sized under static mode, other thermal treatments or Aluminium matrix grade may be investigated to improve Yield and/or Ultimate strength. But it should also be checked that the fatigue behaviour with the new thermal treatment should not be significantly reduced by the static strength improvement.

9. REFERENCES

Ref [1] : *“Modelling the influence of machined surface roughness on the fatigue life of aluminium”* from M Suraratchai, J.Limido, C.Mabru , R Chieragatti from Ecole Nationale Supérieure d'ingénieurs de constructions Aéronautiques – 2008.

Ref [2] : *“Surface characterization and influence of anodizing process on fatigue life of Al 7050 alloy”* from Majid Shahzad, Michel Chaussumier, Rémy Chieragatti, Catherine Mabru, Farhad Rezai-Aria – 2011.

Ref [3] : *“Etude du choix structurel d'outils coupants en diamant revêtu ou polycristallin massif pour l'usinage compétitif et environnemental des composites à matrice métallique et renfort céramique particulaire (CMMP Al/SiC)”*, PhD ENSAM from Arnaud Kremer, 2009

Ref [10] : *“Étude de l'usure par fretting sous chargements dynamiques dans les interfaces frottantes - Application aux pieds d'aubes de turbomachines”*, PhD Ecole Centrale de Lyon, Loïc SALLES, 2010

Copyright Statement

The authors confirm that they, and/or their company or organization, hold copyright on all of the original material included in this paper. The authors also confirm that they have obtained permission, from the copyright holder of any third party material included in this paper, to publish it as part of their paper. The authors confirm that they give permission, or have obtained permission from the copyright holder of this paper, for the publication and distribution of this paper and recorded presentations as part of the ERF proceedings or as individual offprints from the proceedings and for inclusion in a freely accessible web-based repository.