Titanium Rotors in Military Aero Engines - Designed to Weight and Life

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Abstract

Aero engines for military aircraft traditionally have to fulfil the requirement of high thrust to weight ratio, what means that additionally to the high thrust also low weight is required. As the parts also have to withstand significant temperatures, materials with low specific weight but high strength even under elevated temperatures are necessary. The answer is twofold: Titanium alloys for parts under moderate temperature (e.g. compressors) and Nickel alloys for the high temperature region (e.g. turbines).

A further requirement is a component life which allows for a 30 to 40 year engine life. Both requirements together call for the best and latest alloys and for highly sophisticated design and manufacturing procedures.

Cost drivers in the development and production phase are demanding material properties and material quality as well as manufacturing efforts. Production cost can be influenced in the development phase if the criteria of minimum number of parts and design to manufacturing are observed.

Cost of ownership is driven by maintenance efforts and spare part cost. One of the requirements is to reduce or bundle maintenance activities. Another aspect could be a trade off between new parts' cost and parts life.

Cost reduction can be achieved by optimum exploitation of the parts' life potential. The means are improvement of the lifing concepts which should allow for safe extension of life in the crack propagation regime beyond the classical crack initiation life as well as improved accuracy of the life prediction procedures. Accurate records of life consumption under real operation obtained by individual life usage monitoring contribute to cost reduction, too.

Introduction

The Engine Specification defines the purpose and use of an aero engine, covering all aspects of the intended operation. The main requirements are related to the mission profiles to be flown, the power and thrust, fuel consumption and geometric size and weight of the engine. Reliability and maintainability are also of great interest. Thus it is generally expected for a new engine design that reliability is double as high as for the predecessor type while maintenance man hours are halved.

Requirements for the rotors - deduced from the engine requirements - are functionality, life and weight. Rotor lives are often explicitly specified. As in most cases the life limiting damage mechanism in rotors is low cycle fatigue (LCF), rotor lives are measured in cycles. Depending on the intended usage spectrum of the engine the required lives range from 6000 to 25000 cycles.

Generally, rotor weights are to be minimised, with the consequence that any material volume not really necessary for function and life must be removed. Further, rotor parts are exposed to elevated temperatures. From the function of a rotor it is clear that its parts carry high loads at high temperatures and contain high rotational energy. In case of failure they would cause significant damage to engine, aircraft and personnel. High reliability is mandatory and high safety levels are demanded by the airworthiness authorities. That is why most of the rotor parts are classified as 'critical'.

To fulfil all the requirements, high quality materials with low specific weight but high strength even under elevated temperatures are necessary. In engine modules with the highest temperatures (i.e. the turbines) only

Nickel alloys are suitable for these requirements, but in modules with temperatures not as high (i.e. the compressors) Titanium alloys are the optimum solution because they combine high strength with low material density.

Many of these technical requirements are cost drivers; but affordability and hence moderate costs are also required. Some cost reduction is possible with administrative, organisational or logistic improvements, but most of the cost saving measures require technical solutions or at least technical assessment.

Titanium Alloys

Most of the Titanium and its alloys currently demanded are needed for commercial aerospace, where it is used in both airframes and aero engines. Another significant portion is demanded for military aerospace and other military use. Both together account for more than half of the worldwide Titanium production.

Titanium alloys are characterised by high strength and low density, which together provide the basis for component's desired strength-to-weight and life-to-weight ratios. Lower Young's modulus and lower coefficient of thermal expansion (compared to other alloys used in aero engine design) as well as their remarkable corrosion resistance attribute also to their preferred properties. Most of the Titanium alloys exhibit good ductility and are weldable and forgeable.

The Titanium alloys widely used in aero engine rotor design are the following (see [1, 2]):

- **Ti 6-4** (Ti-6%Al-4%V) is a medium strength alloy with good tensile properties, creep resistance and high fatigue strength from room temperature up to 325°C.

- **Ti 6-2-4-6** (Ti-6%Al-2%Sn-4%Zr-6%Mo) provides higher strength and elevated temperature properties up to 450°C.

- **Ti 6-2-4-2** (Ti-6%Al-2%Sn-4%Zr-2%Mo-0.08%Si) has good tensile and creep properties up to 540°C.

- **IMI834** (Ti-5.8%Al-4%Sn-3.5%Zr-0.7%Nb-0.5%Mo-0.35%Si-0.6%C) offers increased tensile strength and creep resistance up to 600°C combined with acceptable fatigue strength.

A parameter often used to demonstrate the strength-to-weight ratio is the breaking length (calculated from tensile strength and density) of a material. This parameter is shown in Figure 1. The Titanium alloys are compared with a Nickel base superalloy which is also frequently used in aero engines.

Material cost prices for these Titanium alloys can be compared as follows. Assuming 100% cost for Ti 6-4, then

- Ti 6-2-4-6 costs around 160 to 170%,
- Ti 6-2-4-2 costs around 125 to 130% and
- IMI834 costs around 380 to 400%.

One can see that higher strength - and particularly higher strength at higher temperatures - increases the material cost prices significantly.

On the other hand it must be noted that the high-strength Titanium alloys are susceptible against hard alpha inclusions and cold dwell time fatigue. In the last years several titanium rotors failed during flight (see [3, 4]) where the failure origin could be traced back to one of these phenomena. But currently, there is no acceptable replacement for Titanium in aerospace and other non-aerospace defence applications.

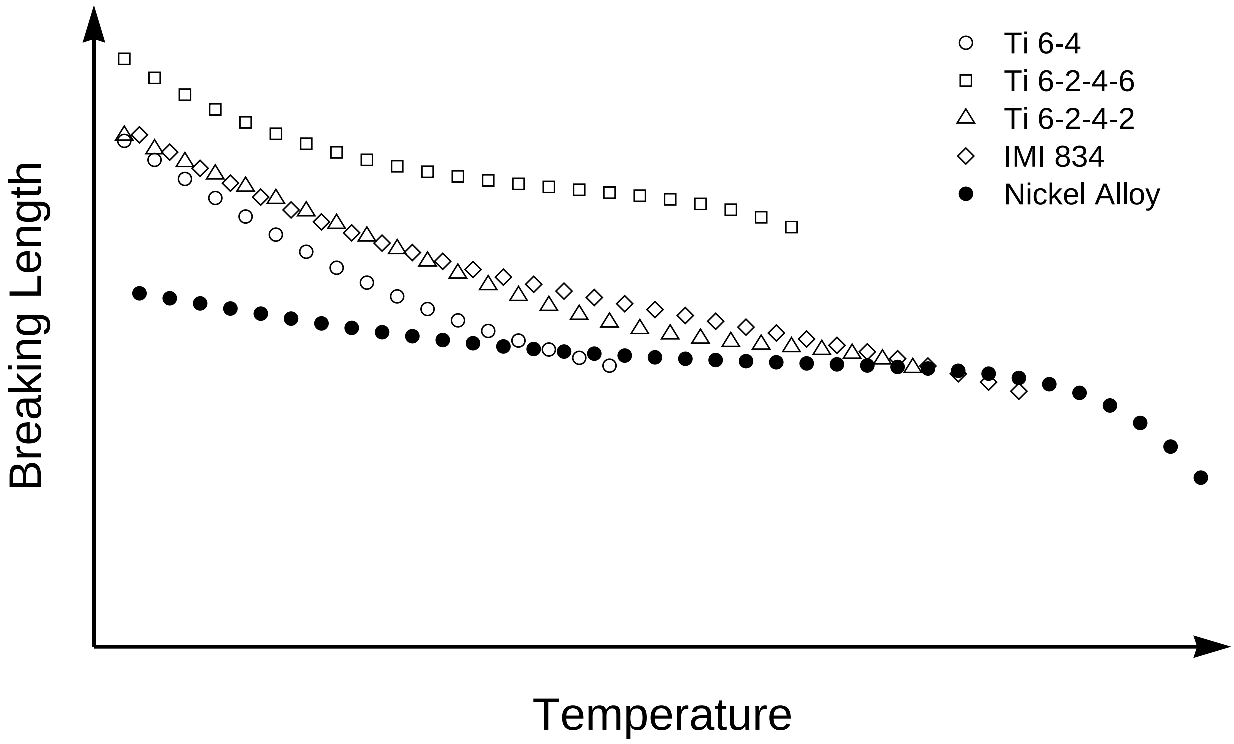

Figure 1: Breaking length of different Titanium alloys (compared with Nickel)

Introducing New Rotor Material

Introducing a new rotor material does not mean to develop a new alloy, but means to make a fully developed new material ready for rotor design. The work includes the issue of a material specification which defines details of the chemical material composition, methods of melting and manufacturing, heat treatment conditions and microstructure, as well as minimum strength properties to be met in material acceptance tests. In the next steps the material characterisation data need to be obtained, which encompass physical material properties, tensile strength properties, monotonic and cyclic stress strain curves, creep behaviour, fatigue lives in the LCF and HCF regime, fracture toughness and crack propagation rates, as well as oxidation and corrosion resistance. These data need to cover the complete temperature range where the components are intended to operate, and also a great variety of test parameter combinations. For many of these data statistical distributions and minimum properties must be established.

We distinguish three levels of data quality:

- the first level is used for general assessment of the material potential; based on this knowledge an engine concept can be initially assessed and a decision is possible whether further investigation into the material promises benefits.
- the second level provides the standard information necessary for detailed rotor design with the capability of safely predicting burst margins and service lives; at this stage statistically confirmed design lines are established, reflecting minimum strength and life properties.
- the third level is the so called integrity level; on this level material data obtained from external sources are verified, or there are data generated required for special design tasks normally not needed for rotor design (e.g. high velocity impact response).

The costs to establish the material data base for a new rotor material sum up to 2 - 3 million Euro. More than 1000 test specimens need to be manufactured and tested. The results must be evaluated and documented, and the final data are to be implemented into the data bases and design tools. The complete procedure starting with the material orders up to the eventual availability of the design data typically lasts more than two years.

Rotor Design

The important parts of an aero engine rotor are classified as critical parts. Critical parts carry high loads at high temperatures and contain in many cases high rotational energy. They are generally life limited. We speak of a critical part, 'where the failure analysis shows that a part must achieve and maintain a particularly high level of integrity if hazardous effects are not to occur at a rate in excess of Extremely Remote' (refer to [5]).

The main design criteria for rotor integrity are burst and life. The burst criterion means that the rotor must not burst even under rotational speeds significantly above the design speed. A minimum burst margin is required to ensure this even in cases where engine control brakes down or the rotor shaft fails. The dominant life limiting damage mechanism in rotor components is fatigue in the LCF regime. The critical areas must safely endure as many stress cycles as are equivalent to the specified engine life. Depending on the purpose of the engine and the intended usage spectrum the required service period of 30 to 40 years requires a life potential of 6000 to 25000 cycles. If it is not possible or suitable to design the rotor for the whole engine life it may be accepted to allow for one or two rotor replacements during the entire service period.

To try a comparison between a compressor disk made of a Titanium alloy and an equivalent made of a Nickel alloy, we conducted some test calculations. The reference for this study was a single medium size disk designed in Ti 6-4. A simulated Nickel alloy disk was chosen with similar geometrical dimensions. But the thickness of the bore region was modified to achieve different characteristics.

In a first step, the thermal stresses for identical geometrical shapes were compared. For a given temperature profile (assuming equal temperature profiles in Titanium and Nickel alloys are physically possible) thermal stresses in the Nickel disk are 2.7 times as high as in the Titanium disk, a consequence of the differences in the coefficient of thermal expansion and the Young's modulus.

In a further step, weight was compared on the basis of different criteria. The weight of the Nickel disk was

- 1.9 times higher for the same geometrical dimensions,
- 1.4 times higher for the same burst margin,
- 1.6 times higher for the same LCF life at the bore and
- 3.4 times higher for the same hoop stress at the bore.

Although we can clearly show the higher weight of the Nickel design, we also see the difficulty that the figures vary widely depending on the chosen criteria. Not to mention that the factors above would be different if the reference design was made from another Titanium alloy. We can conclude that designs in Titanium alloys can generally save weight relative to the Nickel design, but a real comparison would only be possible for a specific design, where a design in Titanium would be optimised to all Titanium properties and a design in Nickel would optimally exploit all Nickel characteristics. However, Titanium is the preferred solution. Nickel would only be chosen if really necessary.

A modern compressor design fulfilling the requirements of low weight and short component length is a concept with a low number of stages, low number of blades per stage and with robust wide chord airfoils. As for such a concept the conventional blade root fixing concept is not adequate, a blisk design becomes necessary. A blisk is a bladed disk where blades and disk consist of a single part. The material volume needed to connect the blades with the disk can be saved. Simultaneously, high stress levels (as would appear in the conventional blade root fixing) can be avoided. The result is a design with reduced weight, increased life and increased reliability.

Considering the experience from the accidents mentioned above, reliability of modern rotor designs will be improved by not using the full range of material strength.

Another very important aspect in state of the art rotor design is to design to manufacture. Manufacturing necessities and manufacturing costs are to be considered already in the early stages of part's detailed design, because around 90% of production costs of a component are determined during the design phase.

Structure Mechanical Assessment

The process of structure mechanical assessment of a rotor component starts from the design mission which is usually defined in the Engine Specification. The design mission provides the required thrust and power as a function of time. It is assumed that at this stage the part geometry and the materials are already defined.

In a first step, there are engine performance parameters derived from thrust and power requirements. The performance parameters consist of the temperatures and pressures in the main gas path and the spool speeds for each point of the design mission. Additionally, the cooling air flows, temperatures and pressures in the secondary air paths are determined.

In a second step, these performance and cooling system parameters are used as boundary conditions for the calculation of transient temperature distributions in the engine components.

The third step is concerned with the mechanical analysis. Total stresses are calculated as sum of centrifugal stresses (due to part rotation), thermal stresses (induced by temperature gradients), stresses from pressures and of assembly stresses (fits and bolt clamping). Based on the results of the stress analysis, the critical areas of the rotor can be identified. Critical areas are those areas which are exposed to the highest stresses and largest stress ranges, and which can be expected to determine the fatigue life of the part.

Finite element (FE) programs are employed for temperature and stress analysis. Since the rotating parts are mainly axi-symmetric, a 2D analysis is usually sufficient. Disturbances of the axi-symmetry (caused by holes and scallops in flanges, arms and cones) are treated with stress concentration factors. Stress concentration factors are also applied for other areas where the FE mesh might not be fine enough.

The second and third step together provide stress-temperature histories at the critical areas over the entire design mission. The stress-temperature histories are analysed with respect to their cyclic content. The most damaging cycle is identified and declared as the reference cycle for the considered critical area.

Concepts to Establish Component Life

Fatigue life of a part is defined as a number of reference cycles (with a given stress range at given temperature conditions) that the life limiting area is able to endure until a crack with specified properties has developed.

The classical method to treat fatigue life is the concept of safe crack initiation life (frequently just called: the safe life concept). ‘Safe’ means in this context that the scatter of material strength is considered and the life of the weakest part of the whole population declared as the life of each member of this population. Under this concept, the majority of the parts will be crackfree at the end of its service life and will still have remarkable remaining life. In most of the cases the crack can be allowed to grow to some certain crack depth before the engine integrity will be jeopardised.

Utilisation of some portion of the 'wasted' remaining life could safe a lot of money, if this potential could be safely used. This led to the idea to extend the service life into the crack propagation phase. The underlying lifing concept is called the concept of safe crack propagation life. This concept is equivalent to that of the safe crack initiation life, but allows a fatigue crack to grow instead of roughly 0.4 mm depth until some other safety criterion is reached. This criterion is called dysfunction. It includes a number of different cases which all could reduce the structural integrity. Of course, the concept does not accept that the dysfunction condition will be really reached, but provides a well defined safety margin.

In both these concepts, the safe life is established as the number of cycles to reach an accepted statistical probability for the existence of a crack with a given depth or for the presence of one of the dysfunction criteria. The statistical probability takes into account that material strength exhibits some scatter. As for the weakest individual of the parts' population the structural integrity must be ensured, the accepted statistical probabilities are in the range of 1 out of 750 to 1 out of 1000.

The criteria of these concepts - namely the existence of cracks - does not mean that the part will fail immediately when the accepted crack depth is exceeded. Some safety margin to the final failure of the part will remain. The parts are not inspected whether the crack is really present when their service life is used up. Only the fewest of them would actually contain a fatigue crack. Nevertheless, re-use of the parts beyond the safe life - as defined above - is not considered.

Experience obtained with the IP compressor and IP turbine of the RB199 engine shows that safe life of a part (in terms of cycles) may be roughly doubled if the crack propagation phase of a fatigue crack can be used. However, one needs to be sure that the critical areas under consideration really provide the necessary damage tolerance. From other critical areas (e.g. spacers in the RB199 HP compressor) it is known that the dysfunction criterion lays very close to the crack initiation criterion (i.e. these critical areas posses only little damage tolerance). For these areas, the only benefit one can take from the damage tolerance concept is the confirmation of a real safety margin (i.e. relative to part failure).

The customer preferred units of life consumption are not cycles but engine flying hours (EFH). To get this information, one has to divide the safe life (in cycles) by a relevant factor which describes the life consumption per EFH (this factor is commonly known as β-factor).

In military applications, the mission profiles contain many sub-cycles. Sub-cycle fatigue damage in the crack propagation phase is higher compared to the main cycle damage than in the crack initiation phase. We see also that crack propagation β-factors are higher than crack initiation β-factors. As a consequence, the real benefit of the life extension concept is somewhat smaller than the gain of cyclic life. For the example above (i.e. RB199 IPC and IPT) the life extension (in terms of EFH) is only 40%. Although this figure is not as high as for the cyclic life, it means still significant cost savings for the customer.

Process of Life Verification

The predicted safe cyclic life for a critical area of a rotor component is verified by cyclic testing. The aim of the test is to verify the crack initiation life of the life limiting critical area. But for other - potentially life limiting - critical areas the test provides results, too. We distinguish between finite results (i.e. where a crack is actually initiated) and non-finite results (i.e. where the cyclic stresses have not yet produced a detectable crack). Finite results are normally obtained for the life limiting critical area. Non-finite results at other critical areas do not evaluate the entire life of these areas, but provide the evidence that these areas possess lives beyond the tested number of cycles.

The test parameters chosen are such that the reference cycle is covered for the critical area for which the life is to be demonstrated. This means that the temperature is very close to the maximum peak (in terms of the most damaging combination of stress and temperature) of the mission. The rotational speed is adjusted to produce a small overload (compared to the engine reference conditions). An equivalent engine life is then calculated from the test result taking into account overload, perhaps temperature correction (if the temperature deviates from the engine temperature under reference conditions) and the features of the underlying statistical model.

Temperature and rotational speeds are monitored continuously during the whole test and vibration measurements ensure safe operation of the test rig. Regular non-destructive inspections (e.g. visual, dye penetrant or eddy current) are carried out to indicate unexpected early cracking. To make sure that the technical crack size of 0.4 mm depth is reached, most test candidates are spun until cracks have a length of several millimeters.

In many cases, the tests produce several cracks. After testing, the most severe cracks are broken up and the cyclic crack initiation life is evaluated by striation counting.

Test cycles corresponding to crack growth beyond the 0.4 mm crack depth provide the evidence for the predicted crack propagation life. An example proving the damage tolerance of a given design is shown in Figure 2 for the RB199 IP compressor rotor. Cracks of up to 40 mm were observed. These tests were accepted to demonstrate the usable life extension beyond the safe crack initiation life.

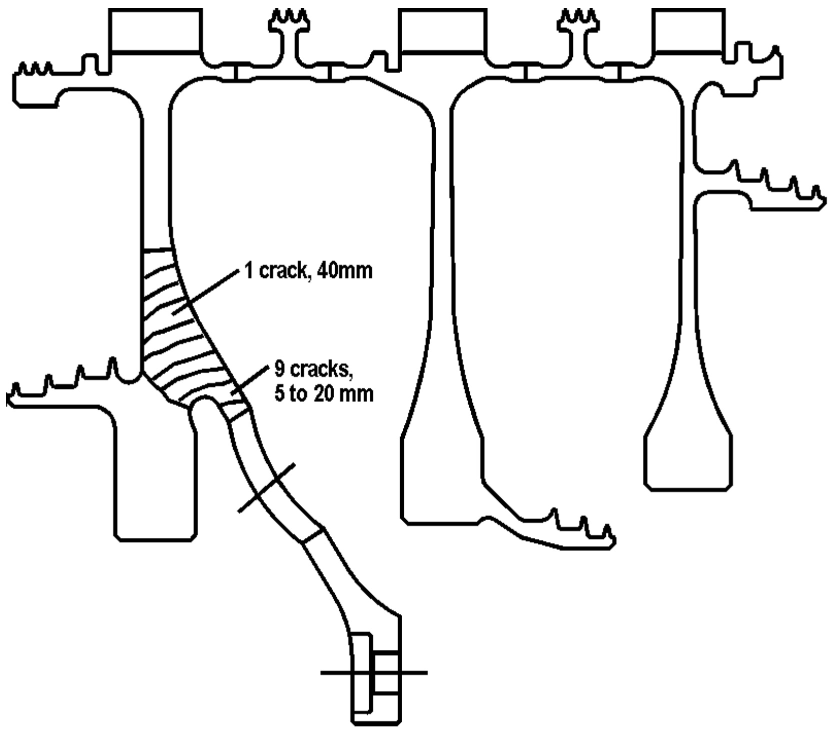

Figure 2: Crack propagation at the RB199 IPC rotor

Re-Assessment and Re-design of a Given Component

Many aero engine projects date back to the sixties, seventies and eighties of the last century. Although state of the art in those days, designs of these projects do not reflect all necessities of today. Many of the parts designed at this time are still in production, either for new engines or for repair of engines having been in service for long time.

During the daily operation a number of problems with the engines have been identified and much experience has been gained. The lessons learnt are not only of great value for new engine designs but could also beneficially used for the recent projects.

One class of the problems is related to the life of highly stressed parts which in case of failure could cause severe damage. Concerned are the components of the rotors, especially compressor and turbine disks, but also spacer rings or rotating air seals. To fully understand the reported problems, it is often necessary to re-assess the design of the components. This re-assessment process concerns mainly structure mechanical aspects and structural integrity. Improved assessment techniques and tools allow in our days investigations which were not possible when the engines were originally designed.

The tools employed for design assessment of aero engine components have undergone significant evolution during the past years. For most of the old engines computer based tools were only available to some limited extent. The limited accuracy of the computation methods for temperatures and stresses were compensated by larger safety margins. With growing computer capacities and increased accuracy it became possible to design components with more evenly distributed stress fields. As older designs show often only a few critical life limiting regions, modern part design produces a higher number of potentially life limiting areas.

One can get an impression of the tool development if one compares the FE meshes illustrated in Figure 3 (taken from [6]). The left hand sketch shows a FE mesh used for axi-symmetric stress analysis during original rotor design in 1979. The same component was re-assessed in 1999 to check for possible life extension. The refined mesh (right hand sketch) takes into account geometric details which could not be resolved with the coarse mesh, with the result that stresses predicted with this finer mesh come closer to the reality. Computing time was also dramatically reduced. While in 1979 the engineers had to wait days for the computation results, in 1999 the analysis could be run within some minutes. One has to admit on the other hand that due to the improved tool capacity a lot of additional load cases could be investigated eating up some of the saved computing time. But this is the price to be paid for making sure that all relevant loading conditions are considered and to obtain greater confidence in the analysis results.

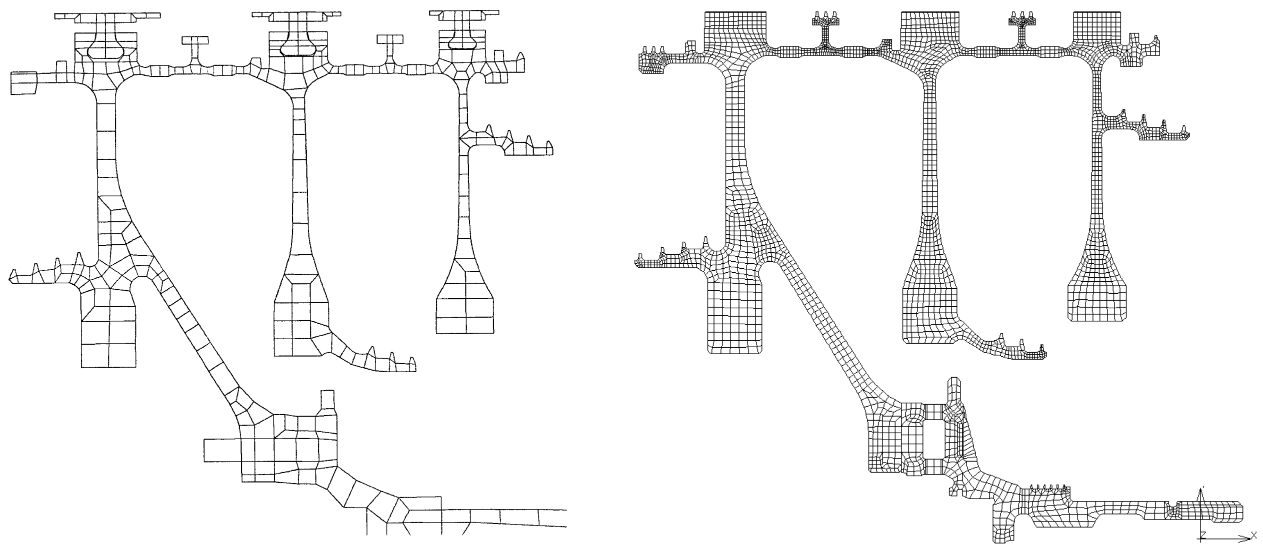

Figure 3: Comparison of coarse (1979) and fine (1999) FE mesh

The necessary invest into new computers and new analysis tools pays back in reduced computing time and reduced assessment time (what can be directly evaluated as saved cost), but provides additionally a more comprehensive picture about component behaviour in service and supports increased confidence in the entire design (what must be considered as an additional not countable value).

Re-assessment of a given design may lead to the re-design of the component. Slight modifications in the detailed design may - for example - relax the stress concentration at critical areas with the benefit of increased component life, if in fact the life limiting areas can be improved. Other problematic areas, not identified in the original design process but found later in the course of inspections of in service parts, can be mitigated or completely avoided.

For many wrought parts it is usual to apply 'near net shape' forging, with the aim to minimise work in the subsequent machining steps. Modifications of such parts are only possible within the given forging contour. Otherwise, the forging process and the dies would have to be changed, too.

The re-design can be also a chance to check the entire manufacturing route if less complex manufacturing processes can be established. A few examples should give us a general impression:

- for certain compressor blades low surface roughness was specified to obtain the required efficiency; however, it turned out that the same efficiency could be achieved with increased roughness.
- changing the reference system for dimensioning of another rotor blade could reduce the rejection rate; quality was significantly improved without additional costs.
- the number of critical features indicated in some design drawings could be reduced to such really necessary; test and documentation expenditure were thereby minimised.
- tolerance bands could be extended for certain geometric dimensions without negative effects to the properties of the components.
- some manufacturing steps (e.g. deburring) which were done manually in the past, can now be replaced by machine manufacturing.

Another point, one should also consider for cost reduction, might be to change the material of the component. Reasons could be that the material currently used becomes too expensive as consequence of declining orders on the world market or is not offered by the suppliers any more. Alternative materials may offer benefits in terms of improved strength and life properties.

But re-design, changes of the production route and material changes do not only provide benefits. The negative side is that additional costs may be caused by verification, validation and certification activities. Generally, major changes at a certified component (and critical parts in aero engines are certified parts) need to be validated and re-certified (see [7, 8]). The expenditure necessary to certify a critical part can be tremendous. A detailed cost and benefit analysis will be necessary to judge whether the intended design changes are profitable.

The situation looks similar for material changes. Much depends on whether the new material is already fully characterised and the appropriate data are in hand. If testing and evaluation of the material characteristics and building up a complete design data base needs to be paid by only one project, then the efforts may easily become higher than the benefits. The time required to build up the data base may also be considered as a stopper.

Operational Usage of Parts Life

Life cycle costs encompass all costs of an equipment from the beginning of its development until its retirement from service. Included are costs related to the development, to procurement (investment) and to ownership. Cost of ownership is associated with the in-service phase. The main contributions stem from consumables (i.e. fuel, oil and lubricants), material (spare parts) and maintenance man hours. Cost of ownership account for up to 60% of the life cycle cost.

An important cost driver for the cost of ownership are the life characteristics and reliability of the engine components. Engine component failure can be caused by a series of damage mechanisms such as low cycle fatigue, creep, thermal-mechanical fatigue, high cycle fatigue and wear. Corrosion and erosion will contribute as well as foreign object damage and secondary damages. Corrosion, erosion and some types of wear can - in principle - be controlled by surface protecting coatings. High cycle fatigue is in many cases caused by vibration in resonance. Resonances can be damped and vibration excitement sources might be avoided by appropriate design measures. Low cycle fatigue, thermal fatigue and creep, however, are usually the unavoidable consequence of the engine's design intent. Improvement of the life characteristics and reliability would not only influence the spare parts costs but also the number of maintenance man hours, since engine stripping and re-assembling would be necessary less frequently.

Sometimes, a trade-off between new parts' costs and parts' life can be beneficial. A detailed life cycle cost analysis could show the most attractive solution. Currently, we observe a situation where military fleets are reduced. This may change the pre-assumptions used in cost analyses. Operators save costs and profitability is newly assessed. The current consequence is that spare parts become abundantly available from the non-used equipment.

In the service phase, cost reduction can be achieved by optimum exploitation of the life potential of the life limited parts. One can say the life potential is used up by life consumption.

The means for cost reduction are:

- improvement of the lifing concept and the life prediction procedures,
- utilisation of a portion of the crack propagation life and
- accurate accounting of life consumption during operational usage.

The critical parts undergo cyclic loading during operational usage. The material experiences fatigue at some highly stressed areas with the consequence of initiation and propagation of fatigue cracks. Growth of these cracks beyond a certain depth increases the probability of part failure. To maintain the structural integrity required in the safety standards, it is necessary to retire a critical part before an accepted risk level is exceeded. When this will be the case, depends on both the released safe life at the critical areas and their life consumption due to operational usage. Different methods for life usage monitoring have been established:

- the traditional method based on flight time and β-factor and
- the individual on-board life usage monitoring system.

The traditional method is to count the engine flight time and to multiply it with a β-factor (also known as cyclic exchange rate). The β-factor provides a relationship between the flight time and the life consumed at a critical area. But the correlation between flight time and cyclic life consumption is very weak and the β-factor therefore only a crude measure for in service life consumption. Some conservatism needs to be incorporated into the β-factor, what in turn leads to overestimation of life consumption for most of the parts.

In reality, the life consumed during an engine run or flight is based on stresses and temperatures at the critical areas of the components. These parameters depend obviously on the actual mission profiles, engine intake conditions, individual pilot reactions and many other influences. Thus, one can conclude that better exploitation of the released life is achieved with individual monitoring, where life consumption of each part is individually calculated using actually measured engine parameters.

The procedures for individual monitoring reflect the process of structure mechanical design assessment, but consist of effective algorithms for use in real time, able to calculate the consumed life directly from measured engine signals. The algorithms allow for fast transition of the input signals as they appear under real aircraft and engine manoeuvring. Results are available immediately after the end of a flight. Life usage is measured in damage related physical or technical units.

Details of the method have been published at several occasions (refer to [9, 10, 11]). Here only a short summary is given. The method determines the thermal and mechanical boundary conditions for the engine components on the basis of measured time histories of engine operating parameters (such as spool speeds, intake conditions and gas path temperatures and pressures). Based on these boundary conditions, the transient temperature development within the components is calculated. Stresses or strains at critical areas are computed, which are then used together with the corresponding temperature histories to predict the related damage. Critical area damage is accumulated over all engine runs, so to build up complete life consumption records for all monitored parts of an engine.

The procedures for individual life usage monitoring outlined here (which are basically also applied in the process of determining β-factors for traditional life usage tracking) are closely related to the life prediction process which is part of the entire engine development process.

The introduction of a fleetwide life usage monitoring system able to count life consumption individually for all relevant parts of each engine of that fleet means a significant invest. On the other hand, the savings gained with such a system pay back several times.

One can get an impression of the situation when looking at Figure 4 showing the frequency distribution of relative life consumption. A scaled depiction has been chosen to allow for the inclusion of all monitored areas of the engines. Life consumption is shown relatively to the mean value. The data describe the typical operational life consumption of a whole fleet. The curve shows a wide scatter (around one order of magnitude). From that scatter it becomes clear that a measure of life consumption using flying hours and β-factors would not be adequate. The cyclic exchange rates would have to be selected from the upper tail region of the usage distribution. This would be necessary to minimise the risk of using parts beyond their released safe life limits. However, some remaining risk would need to be accepted. Such a high β-factor would drastically overestimate the life consumption of the bulk of the distribution. This life potential would be simply wasted. In contrast, individual life usage monitoring figures out correct life usage (despite some uncertainty due to algorithm inaccuracy) of all individual parts. A detailed evaluation shows that in average the parts can be kept in service roughly twice the time as they would without individual monitoring. A side effect is that the overall risk of using a part in excess of its released life is avoided.

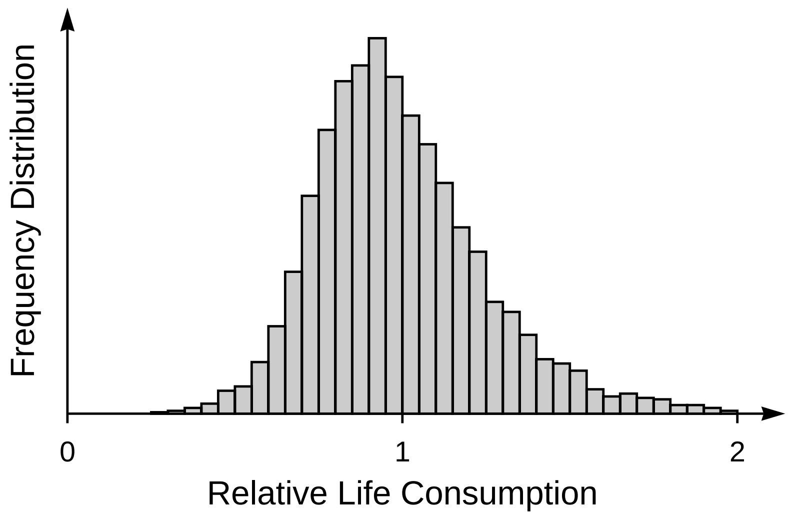

Figure 4: Frequency distribution of life consumption

Conclusion

Titanium alloys are - one can say "traditionally" - used in aero engine compressor rotors. Their particular characteristics (i.e. high strength and low density) are optimal to fulfil the requirements for high strength-to-weight and strength-to-life ratios. However, titanium alloy suitable for higher stresses at increased temperatures are drivers for costs.

High costs and high quality components seem only affordable if their inherent life potential can be optimally exploited during he service phase. Improved concepts to establish component life and improved methods to monitor life consumption are as important as cost reduction measures in the design and manufacturing processes. Costs can be saved and must be saved in nearly all phases of an aero engine life cycle.

Acknowledgement

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