Titanium in Aero Engines

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Abstract

The talk is intended to give an overview on the necessity and future trends of titanium parts in aero-engine applications. It will serve as a link to the presentations given in the special session aero-engines.

It is well known that for aero-engines the combination of a very high loading by temperature and stress together with extremely high safety levels are determining the choice of materials and the requirements for their quality. Whereas the growing consciousness concerning environmental pollution implies the same challenges just stated, the constant competition in the aero-engine industry results in an increasing pressure on manufacturing and life-cycle costs.

The main properties that have caused the triumphal march of titanium alloys into aero-engines over the last five decades are its high specific strength, together with good corrosion resistance and weldability. Today's broad applicability can be illustrated with examples of different type of parts made of titanium, where the special needs of the location in the engines results in several special niches for the different classes of alloys.

The future trends may be divided into two categories, namely the development and introduction of new materials with improved properties and the cost-reduction activities for the manufacturing process – from the raw material to the finished part. For the new materials, their ecological niches will be shown, mainly determined by the material properties. However, an emphasis will be laid on the fact that besides material properties many important accompanying issues have to be clarified to evaluate the suitability of new alloys. For the cost reduction issue, the steps of the manufacturing process, together with relevant parameters to optimize profitability, will be presented.

1 Introduction

With a volume fraction of approximately forty percent, titanium alloys are one of the three material groups (besides nickel superalloys with forty percent and steels with twenty percent) dominating aero-engines. This is true now for several decades and there no reason can be seen why this situation should change in the near future.

What are the wishes of aero-engine customers that, in the end, result in the choice of a titanium alloy (and its manufacturing process) as the structural material for specific engine parts? The customers are the airlines and their passengers. What they want is quite similar to what we expect from an automobile, i.e. a *maximum functionality* together with *minimum costs* for buying and using the vehicle. And as we want to get a car as soon as possible, after we have decided to buy it, the *time from launch to delivery has to be a minimum* too. But there is an additional criterion, which is felt to be much more important when entering an aeroplane and which is documented with more accuracy in the newspapers: *safety*.

We will now try to get a feeling of the trends concerning these three criteria and to learn which are the corresponding parameters for materials and processes. This gives us the basis to understand choices of titanium alloys today as well as the presented future trends. It will also help the engineer to weight the possible ways of development and choice of materials and processes by himself.

2 Demands on Titanium Alloys and Processes in Aero Engines

2.1 Safety

Starting with the "condition sine qua non", safety, let us have a look at the past and future of the air traffic volume together with the relevant engine failures. Figure 1 shows these parameters with respect to time. First of all it should be noticed that the relative frequency of uncontained failures (i.e. parts are penetrating the engine's casing and may therefore endanger passengers and/or airframe) with respect to departures has decreased considerably over the last decades. In fact, the probability of staying alive travelling from location A to B is a hundred times better using an aeroplane rather than a car. But Figure 1 shows also that the air traffic is increasing steadily (as expected after getting back to "normal conditions" when the effects of September 11th have past). On the other hand, as a demand of governments and the public consciousness, the absolute values of relevant failures should not increase. *That means that the safety level of the engine has to improve!*

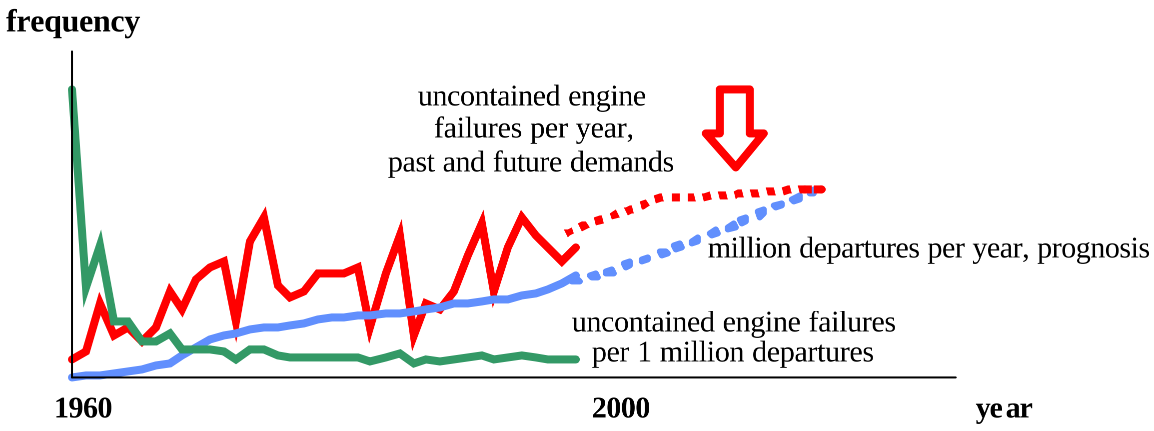


Figure 1. Development of Air Traffic and Relevant Engine Failures in the past (Source: FAA) and demands for the future.

What are the aspects related to materials and processes which allow us to influence the safety of the engine? First of all the detailed *knowledge of the materials behaviour in the engine*, whereby also material qualities which have some acquired damage, have to be regarded. Here, today's time schedules in most cases require the *ability for analytical simulation* rather than time consuming tests. This is one of the fields of research where materials and process science have to perform a wide step to be in line with other disciplines of the design procedure. Another important influence on the safety level is given by the *damage tolerance* of the material and its design concept. Configurations where materials are assumed to have no deviation from optimum quality, and where they are loaded to the very limits for this optimum quality, as well as those cases where a premature start of becoming damaged or degraded leads quickly to fatal damage, must be avoided. A third way to influence safety is to improve the *stability of the manufacturing process* together with a higher *accuracy of the quality testing*. Precise lifing prognosis and certification tests do assume that the material will be as was specified (and certified)!

2.2 Functionality Including Life Cycle Costs

Let us now shed some light on the functionality item where life cycle costs have to be included because of their strong interdependence to "technical" properties, which can be seen by the fact that both result in the same parameters of materials and processes. Customers need engines with

- *high thrust* to have high manoeuvre capability and to power aeroplanes with higher weights (i.e. with more passengers) or with two instead of four engines,
- *low weight* to avoid unfavourable center-of-mass effects (where, for military applications, the engines' mass is up to 15% of the whole aircraft) and to reduce fuel consumption,
- *high efficiency* to reduce fuel consumption,
- *low noise and emissions* to fulfil governmental and airport requirements (e.g. the number of take-offs per airline is limited to a maximum value for the sum of noise and emissions of all the airlines' aircrafts), and
- *low life-cycle costs*, i.e. low fuel consumption, long life and repairability of parts.

Looking at the possibility for materials and processes to support these needs, all of these engine specification parameters translate to only a few well-known main material and processing properties:

- *high ratio of "strength" to specific weight* for low weight of parts and long lives (where "strength" stands for static, cyclic and viscoplastic properties)
- *high temperature resistance* for long lives and to realise high engine temperatures
- as many *degrees of freedom for design* as possible to allow 3D airfoil geometry and to realize new design concepts

For the design engineer, of course, a lot of other criteria such as the *physical properties* and the availability of *approved manufacturing and quality processes* limit usable alloys and processes.

2.3 Engine Price and Time to Delivery (i.e. Costs and Lead Time for Development and Production)

A safe engine which fulfils all its specified functions perfectly will nevertheless not be sold if its price is too high or the date of delivery is too late. As simple as this statement may be, it is *as* difficult to be aware of its consequences at all times during the development of an engine. But this awareness is more important than ever before in engine business, because competition is getting tougher and therefore *allowable costs and lead times have decreased*. The main reasons are a reduced market volume due to September 11th, as well as the fact that more and more engine parts which were "high tech" in former times, can now be provided by low-cost manufacturers. An additional pressure on development costs and duration is caused by the increased ratio of commercial to prepaid military business, since for commercial engines the time from programme launch to positive return of capital has increased to about fifteen years (due to longer part lives, higher technology & development costs, and high price concessions for engines).

The possibilities for a materials and process engineer to help reduce costs and duration of development and production concentrate on optimizing *manufacturing* processes to *reduce process times* and *process steps* as well as to develop *more process stability* (i.e. reduction of required quality testing and higher output rate). An effective way to support the quality and quickness of this optimization is the availability of analytical *simulation tools for materials behaviour and processes.* To ensure process stability criterion, one of the design engineer's main duties is to choose only materials, vendors, and manufacturing processes of a maturity which has proved to make "unpleasant surprises" unlikely. Finally, the choice of the *cheapest material* fulfilling functional requirements is the most obvious and usually well-done task of the designer.

2.4 Summary of Materials and Process Engineers Parameters to Address Customers' Demands

Figure 2 sums the results of chapters 2.1 to 2.3 for quick reference. Please note that this table is true not only for compressors (nowadays the domain of titanium alloys) but also for the turbine. The differences arise only if one goes into the details of the dominating damage mechanisms and the absolute temperature level.

	safety	functionality and life cycle costs	engine's price and time of delivery
material (incl. design concept) parameters:			
physical properties		■	
specific strength (incl. static, cyclic and viscoplastic properties)		■	
temperature resistance		■	
degrees of freedom for design		■	
damage tolerance	■	□	
quality of material data and ability of analytical simulation	■	□	■
material costs			■
process (manufacturing and quality testing) parameters:			
process stability (incl. sufficient maturity)	■		■
number of steps and their duration			■
availability of process simulation			■
accuracy of quality testing	■		□

Figure 2. Correlation of materials and process parameters with respect to customers' demands

3 Titanium Alloys in Today‘s Engines and Future Needs

This chapter is intended to give an overview on the distribution of titanium alloys in a typical aero-engine. With the added information on the chosen alloy's advantages as well as the limiting features compared to other alloys it shall be shown that the available variety of titanium materials is justified due to a lot of “ecological niches” in the engine environment. Furthermore the future requirements will be addressed to understand the new developments presented in the next chapter as well as to give basic information to the creativity of scientists and engineers involved in materials and process development.

All this information has been put into figures 3 and 4. To come to understandable groupings we divided all Titanium alloys used in aero-engines into “classes”, where the “classification” is due to the first two criteria of choice, namely temperature capability and costs of the material. The explicitly-named alloys are to be understood as representatives for all “sister-alloys” within the class. As an example the Ti-17 alloy is covered by the Ti-6246-class.

Starting with figure 3, the main classes are listed with respect to increasing temperature resistance (which in general goes with the material costs, otherwise it will be mentioned in the list). On the figure’s right hand side the (simplified) main advantages and disadvantages for choosing the alloy are added. Furthermore the limits of Titanium are given, i.e. the competitive material classes and the reason to change from Titanium to them. Note that every class has its advantages, which is what we meant by the above mentioned “ecological niche”.

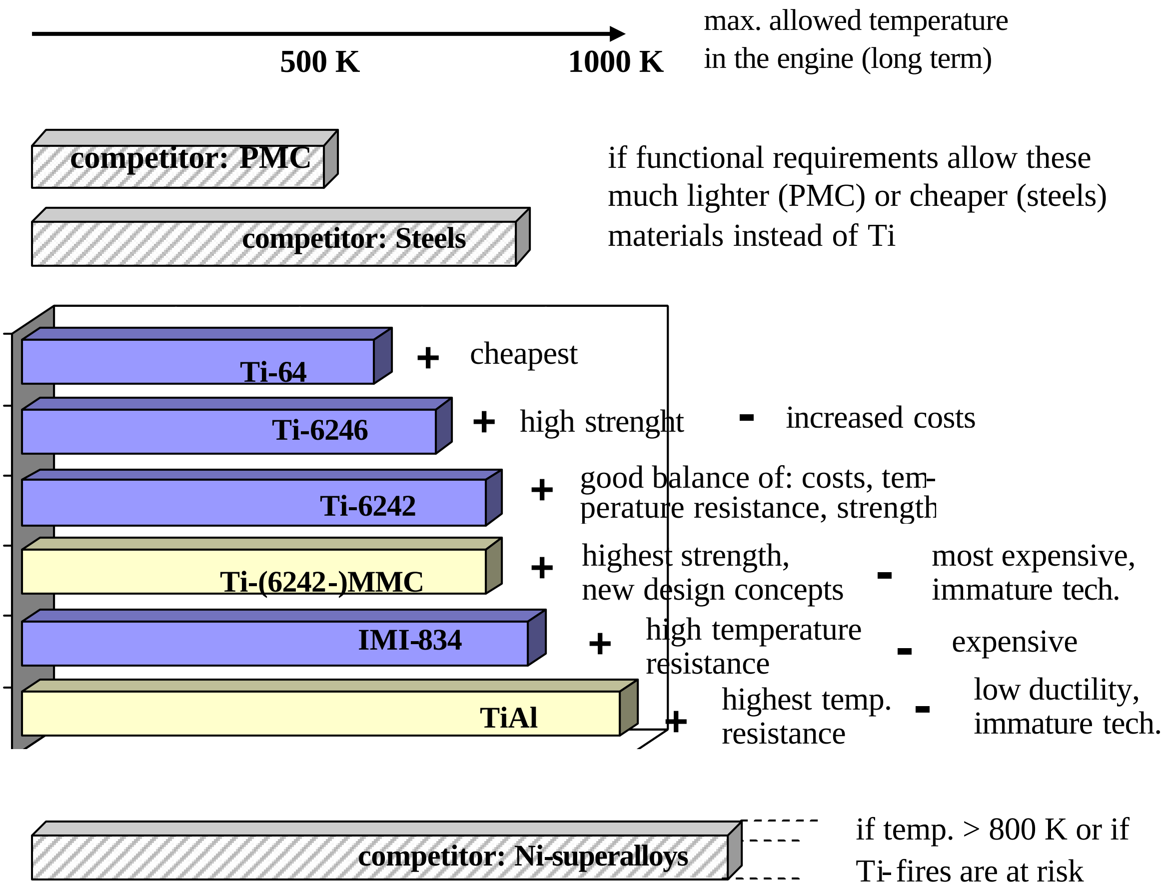
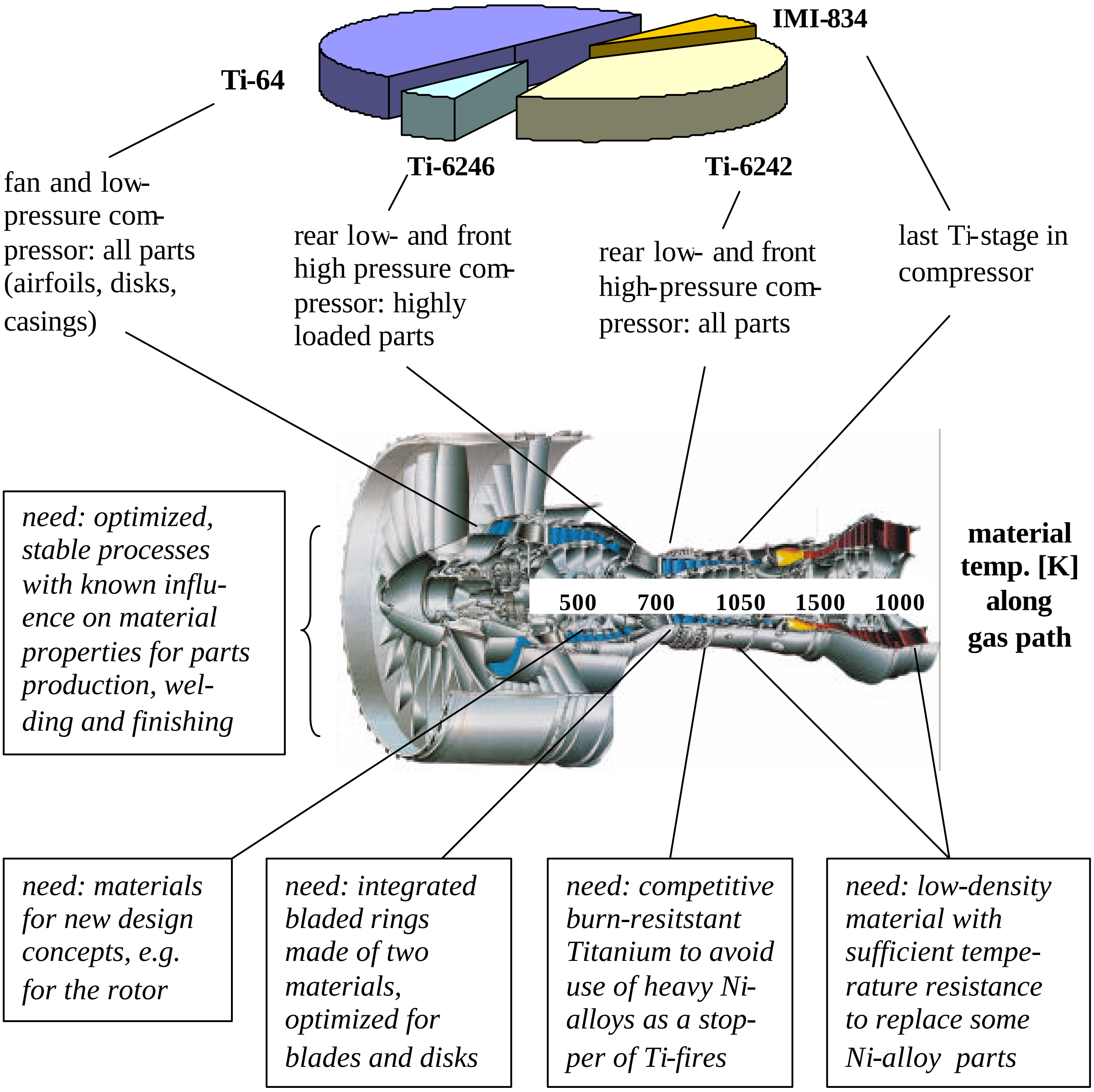


Figure 3. Main engine-relevant material advantages and disadvantages of Ti-alloy-“classes” (where the explicit named alloy represents all alloys with comparable properties, e.g. Ti-6246 stand also for Ti-17). Bars of immature technologies are white. On the top and bottom of the figure the competitive materials and the reason for using them instead of Titanium are added.

In the upper part of figure 4 is shown which volume fractions of the Ti-alloy-classes result due to the requirements of the engine. Driven by its low cost and, last but not least, because of the long experience with the alloy, Ti-64 is used in any case where the service temperature allows it. For higher temperatures Ti-6242 is the standard material and therefore holder of the second position range. Ti-6246 and IMI834 are materials for special purposes (i.e. going to functional limits of Titanium in strength and temperatures, while accepting higher costs) and therefore not used in all engines. In the remaining part of figure 4 locations of engine parts made of the mentioned alloys are illustrated together with future requirements going beyond the potential of today's alloys and pushing the new developments described in the next chapter.



fan and low-pressure compressor: all parts (airfoils, disks, casings)

rear low- and front high pressure compressor: highly loaded parts

rear low- and front high-pressure compressor: all parts

last Ti-stage in compressor

need: optimized, stable processes with known influence on material properties for parts production, welding and finishing

need: materials for new design concepts, e.g. for the rotor

need: integrated bladed rings made of two materials, optimized for blades and disks

need: competitive burn-resitstant Titanium to avoid use of heavy Ni-alloys as a stopper of Ti-fires

need: low-density material with sufficient temperature resistance to replace some Ni-alloy parts

Figure 4. Upper diagram: today's volume fractions of Ti-alloy-"classes" (see figure 4) in an aero-engine. Immature materials are not included. In the lower part of the figure examples for Titanium-made engine parts and some future requirements beyond the standard materials are given.

4. Some Developments in Titanium Materials Research With High Relevance to Aero-Engines Applications

This last chapter acts as a link to the papers dealing with new Titanium materials in this aero-engine session. The basis of the link are the needs addressed in chapters 2 and 3. In addition we want to remind that new ideas are only applicable if *all* requirements mentioned before (for example proven-process-stability for a new material or process) are fulfilled and must therefore not be forgotten in the euphoria of new developments.

Need: Optimized, stable processes with known influence on material properties for parts production, welding and finishing. Many process steps are necessary to transform the raw material to the engine part having the specified geometry and material properties. These processes involve the main potential for cost and lead time reduction and therefore optimizations are always to be pursued. Furthermore every new material requires all its process steps to be developed, fitted, or just validated. As an essential task it has to be ensured that the new process is stable and the process-specific influence on the bulk material properties is known. The following papers of the aero-engine session deal with this matter for raw parts production [1], [2], [3], for parts welding [4], [5] and for machining manufacturing processes [6].

Need: Materials for new design concepts, e.g. for the rotor. Increasing thrust and life requirements may force the engineer to design heavier parts, unless a material with considerably higher strength is available. However, with such a material he even may overcome the problem with a new design concept, e.g. increasing the inner diameter of disks. In future applications a material may be a fibre-reinforced Titanium (Ti-MMC). Of course such a material may serve also for other kinds of parts, where the loading is mainly unidirectional. Main challenges are high development costs, realization of competitive production costs, ability to detect relevant defect sizes by non-destructive quality testing, and a safe life concept. For more details see reference [7].

Need: Integrated bladed rotors made of two materials, optimized for blades and disks. Integrated bladed rotors (IBR), i.e. disks and airfoils made as one part, are nowadays indispensable design concepts, since for some stages the increased loading results in unacceptable stress conditions at the airfoil-disk contact area for the conventional two-part design. As a disadvantage of IBRs, one has lost the freedom to use different materials for airfoil and disk to take into account the different dominating damage mechanisms in the compressor (airfoils: high-cycle fatigue, disks: low-cycle fatigue). Therefore, the next step is to develop stable welding processes to “glue” optimized airfoil material to optimized disk material to build an integrated bladed ring. A project supported by the European Union is investigating this matter.

Need: Competitive burn-resistant Titanium to avoid use of heavy Ni-alloys as a stopper of Ti-fires. In modern aero-engines, the parameters in the high pressure compressor are always such that a Titanium fire may occur. Therefore, besides other measures (such as casing-coatings to keep an ignited fire inside the engine) designers choose Ni-base alloys for vanes as a barrier in the axial direction. This means a weight increase although the temperature resistance of Titanium would be enough. The more comfortable way to prevent the engine from Ti-fire problems is to use competitive Titanium alloys which are burn resistant, described in reference [8].

Need: Low-density material with sufficient temperature resistance to replace some Ni-alloys parts. As weight reduction is always a main goal of engine design, the offer of a Titanium alloy which has the potential to replace Ni in a stage is always a interesting issue for the designer. Since the limited temperature-resistance of Titanium forces the use of Ni-superalloys we need a Ti-alloy which expands the limit. This is the domain of Titanium Aluminides. However, with respect to aero-engines requirements, two questions need additional investigations: Is the material's ductility sufficient for the application and how can design engineers be convinced that this is the case? Can the manufacturing process be changed or just stabilized to end up with competitive costs? Reference [9] will deal with Titanium Aluminides in aero-engines.

5. Acknowledgements

Usually a paper which is intended to give an overview is based over a longer period of time in the past with a lot of discussions including many people. Therefore I want to thank all those who had enough patience to help me understanding the main correlations between engines' requirements and material properties. The sometimes hard but necessary simplifications for this overview can be seen as a last test for their patience. Surely D. Helm is the one whose advice I made use of most. Special thanks to him!

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