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INTRODUCING NEW MATERIALS INTO AERO ENGINES - RISKS AND REWARDS, A USER'S PERSPECTIVE

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Abstract

Developing and certifying new aircraft engines is expensive. Once introduced, an engine will have a life measured in decades, and manufacturers and users are reluctant to introduce changes for a number of reasons, not least of which are safety, reliability and cost. Thus the opportunities for new material introduction are few and the consequences of an imperfect decision are high. It is therefore imperative that materials engineers utilize any opportunity to introduce material improvements that are presented. This paper will discuss the risks and necessary actions to achieve successful material insertion and will give examples and attributes of successful and unsuccessful alloy development efforts.

Introduction

Aero engines require specialty materials that can withstand the demanding environments imposed on the various components and sections that ultimately provide energy and thrust. In general, aero engines require materials that are lightweight, high strength, damage tolerant, high temperature capable, oxidation and corrosion resistant with robust, repeatable mechanical properties that can be readily manufactured into components that are inspectable to ensure the required level of quality and mechanical capability. These requirements are also bounded by the absolute need for lowest possible cost and greatest possible availability.

The need for new alloys stems from changing engine requirements in both technical and commercial areas. Materials can be significant enablers for new engine architectures and engine cycles. In general, increasing temperature of a turbine engine increases the efficiency and performance, which in turn reduces mission fuel burn, operational costs, and increased engine performance capabilities. The goal to increase efficiency and performance is requiring the need for new materials to meet the demands of these new engine environments.

Equally important to material capability is the affordability and availability of new alloys for new and legacy engine applications. The cost of alloys has a significant impact on alloy selection and hence optimization for engine architecture, cycle and overall engine efficiency and performance. Costs can also be influenced by alloy availability or total market demand, such that low volume specialty materials or materials with additions of low availability elements can make useful, capable alloys unaffordable.

Traditional alloy development has been conducted by original equipment manufacturers (OEMs) as well as raw material producers, by trial and error methods to meet a single set of requirements for a specific application. The development of alloys by OEMs has resulted in alloys that are specifically tailored to the need of the particular engine manufacturer developing the alloy.

Optimization of alloy chemistry and microstructure for a specific application has been traditionally very technically successful, though the application of OEM-developed alloys has been traditionally limited to the developer of the alloy.

Alloys developed by raw material suppliers are often more widely used by many, if not all, of the engine OEMs. These alloys can be developed to meet the general requirements for sections of the turbine engine and can be utilized by different companies in similar or in some cases completely different manners, depending on engine architecture and requirements.

In the past, engine OEMs have often developed alloys with the support of government-funded programs, which reduced the cost of alloy development for any one company. Current and future alloy development will likely be a collaborative effort, where companies with common requirements will work together to develop a new alloy that can be jointly utilized for specific applications for each company's turbine engines. This approach provides three major benefits: 1. Reduction of alloy development cost for any one OEM, 2. Reduction in costs to develop a specification and associated material property databases, and 3. Increased use of the new alloy, whereby making the alloy lower cost with increased supply-chain volume.

For aero engine applications, the safety and reliability requirements are such that extensive knowledge about the material pedigree, sources of variability and potential failure modes must be well understood and carefully controlled. This traditionally results in requirements for extensive database generation from large volumes of material to ensure capturing production variability and capability before certification of a new alloy and application to critical components.

General Material Requirements within a Gas Turbine Engine

Turbine engines in general operate in a similar manner. The inlet side draws in air through a fan where it is compressed within the compressor section, mixed with fuel and burned in the combustor. The resultant combustion products are expanded through a high pressure turbine that drives the compressor section of the engine and through a low pressure turbine that drives the fan section of the engine. High bypass ratio turbine engines produce a large fraction of thrust from the large fan, while low bypass ratio engines provide thrust through the high velocity exhaust of the engine core. Figure 1 shows an example of the general materials that makeup an advanced 3-shaft high bypass ratio commercial engine.

For aero engines, unlike land-based power generation engines, there is an enormous drive for light weight materials and structures to reduce the parasitic weight from the engine to enable greater aircraft efficiency (i.e. less energy required to lift and carry the engines). Lighter alloys are sought for this reason. Aluminum and magnesium are of great interest from the standpoint of their low density, but their strength and temperature capability limit their applications on aero engines. Titanium, however is an alloy class that is significantly utilized within aero engines due to its low density as well as applicable strength and temperature capability. There are many alloys of titanium, but one of the first alloys ever invented in the early 1950's, Ti-6Aluminum-4Vanadium, is still the most widely used alloy for aero engine applications.

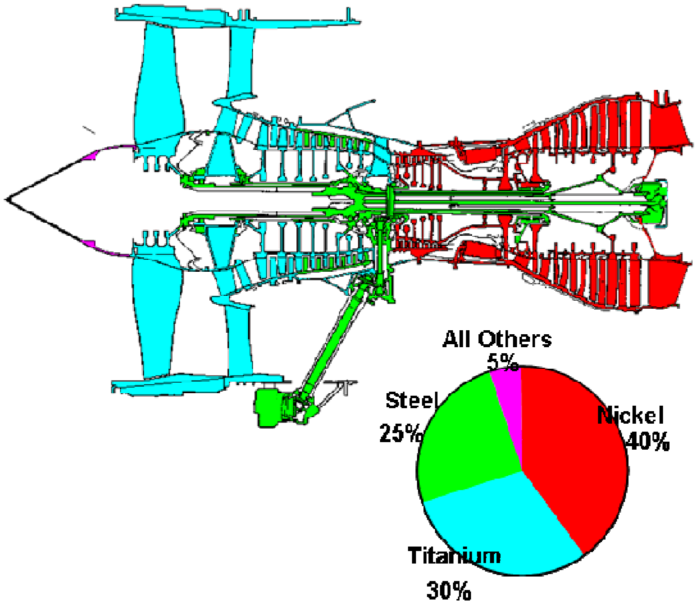

Figure 1. Location of various alloy types within an advanced 3-shaft turbine engine. Lower temperature sections readily use low density materials such as titanium, but as temperature increase, nickel-base superalloys prevail.

As temperatures increase within the compressor, the demands on materials increases. Titanium alloys have been developed to meet these demands and have resulted in alloys such as Ti6246 and Ti6242. The highest temperature titanium alloys developed for turbine engines are Timetal-834 and Ti-1100. Timetal-834 (formally IMI834) was originally design and developed by Imperial Metals and has been available widely to the entire aero engine community. Ti-1100 was subsequently developed by Timet to meet the highest temperature needs for a titanium alloy, however the return on investment by OEMs to qualify this alloy has resulted in limiting its introduction and use. As titanium alloy mechanical property capabilities increased their resistance to oxidation and burning did not, limiting the upper temperature for their use.

The later stages of compressors have increased to a temperature that titanium can no longer be utilized. Cast and wrought nickel-base superalloys, such as Alloy-718 and Waspaloy are being used along with powder metallurgy nickel-base superalloys, such as RR1000 for compressor disks. Similar increases in alloy capability are required for compressor blades and vanes, where traditionally no cooling schemes are used to mitigate the increasing temperatures of the later stages of the compressor.

The high pressure turbine region experiences very high temperatures. The high pressure turbine disk must be able to withstand these high temperatures and the extensive centrifugal loads from the rotating disk itself as well as the cooled airfoils that are extracting energy from the high temperature, high pressure and high velocity gas flow path.

Like the later stages of the compressor, the low pressure turbine section of aero engines requires high temperature capable materials that are often not actively cooled. This section of the engine often calls for alloys like U720, Waspaloy or Alloy-718.

Many attempts to develop and introduce commercial, higher temperature titanium alloys based on the intermetallic compounds TiAl and Ti3Al have been conducted. Development of a commercially and engineering viable TiAl alloy for aero engines has been pursued for nearly 40 years. Development efforts for gamma-TiAl alloys have seen ebbs and flows in progress based on government funding availability, breakthroughs in fundamental understanding and strong commercial pressure for such an alloy. This material is currently seeing its first introduction into aero engines within the next-generation commercial engines. Figure 2 shows an example of a low pressure turbine blade produced from a gamma-TiAl alloy. The higher temperature capability of this titanium-based alloy and its low density can provide significant benefit to the overall performance of turbine engines.

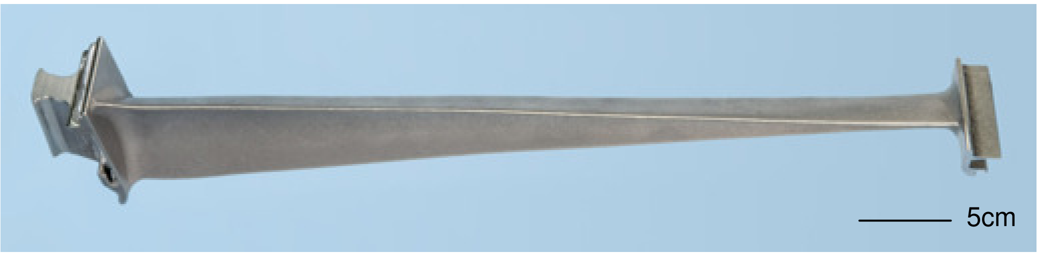

Figure 2. A photograph of a large low pressure turbine blade that is being qualified for a next generation commercial aero engine. After many programs and extensive alloy and process development by many companies and organizations, this alloy class is now seeing applications within several aero engines.

Like disks and airfoils; cases, shafts, bearings, gears and structures have unique requirements that drive alloy development toward specific balances in material properties. The issue of new alloy development and application is one of material capabilities and economics (both in alloy development and qualification).

Alloy Development Approaches: Past, Present and Future

There are extensive barriers to the development of new materials and alloys for aero engine applications. The costs of alloy development itself are very large. Traditional alloy design methods included trial and error experimentation. Laboratory-sized samples of materials were often used to screen the capabilities of potential new alloys. Once an alloy or series of alloys was identified, it would be scaled-up to subscale trial quantities that could be manufactured into small amounts of bulk materials for assessment and characterization of a large range of properties. For those alloys that made it through the subscale assessment phase, full-scale trials were performed to determine if the previously observed properties would be maintained at full-scale. This step in traditional alloy design was nontrivial. It is sometime noted, “The first thing you hear about a new alloy is always the best thing”, which often shows itself true during alloy scale up, and where further challenges arise during subsequent alloy development stages. In traditional alloy design methods, the scale up process introduces new variables that were not foreseen or mitigated during subscale efforts, such as the extent of alloy segregation, aim alloy chemistry control, microstructure control, etc.

The cycle time to develop new alloys have been extensively out of sync with turbine engine design cycles. A <24-month engine design cycle is not atypical, but alloy development times are much longer; for example typically 10 years for disk alloys and 5 years for airfoil alloys based on traditional alloy design and development methods.

The cost of alloy development programs can also be insurmountable. Costs in excess of $100M for a new disk alloy are possible. Advanced alloys developed in the past have often been accomplished through support of government agencies. The P/M nickel-base superalloy Rene'95 started out with an extensive number of alloy development program to study chemistry and processing effects. [1] Similar efforts have been seen through the more recent NASA-sponsored Enabling Propulsion Materials (EPM) program where a large portion of the approximately $200M program was utilized to develop a new P/M disk alloy called ME3, which is now currently in production at two engine OEMs. [2]

Alloy development efforts have also been conducted by raw material producers. Advanced titanium alloys were developed in the past to meet increasing application requirements. Alloys Ti6246 and Ti62222 were developed with support from Air Force sponsored programs. The former was developed and implemented into disk applications directly from these development efforts, whereas the latter found a home much later in the form of airframe structural components.

Alloy producers also developed many alloys through 100% in-house research and development. Many superalloy material producers had extensive research laboratories aimed at investigating ways to enhance the capabilities of their materials, such as for corrosion, high temperature capability and overall mechanical properties. These efforts resulted in many superalloys that were adopted by many OEMs, such as the Incoloy, Inconel, Udimet and Hastalloy alloy families to name a few. Inconel-718 (Alloy-718) was developed by Inco Alloys and has been a staple in nearly every turbine engine since. The benefit of alloys having been developed by a material producer is there is a large push for the alloy's general and widespread use. Alloys developed by an OEM are often held tightly as a potential competitive advantage over other OEMs.

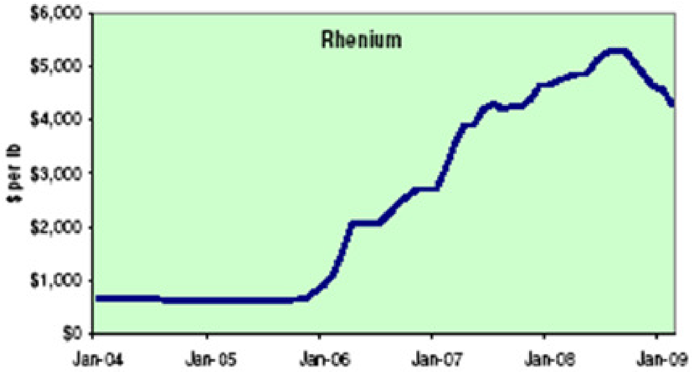

Figure 3. The market price for rhenium, which shows considerable fluctuation and increase in price due to market pressures for this limited-availability material.

In addition to the economy of scale, there are other cost factors that need clear notice and tracking during alloy development, namely use of strategic or low availability alloying elements. For certain alloy capabilities, specific alloying elements are required, but these elements may drive the overall cost and availability of the final alloy. Rhenium and ruthenium are examples of important elements in single-crystal nickel-base superalloy development, but the cost of these elements is making alloys that utilize these elements unaffordable. Market pressures also make the cost of such alloys uncertain and difficult to forecast. Figure 3 shows an example of the market price trend for rhenium.

Reduced alloy development funding within OEMs, material producers and from the government has recently resulted in many fewer alloys being developed. The increased cost imparted by limited volume usage of single-OEM materials is also becoming economically challenging and nearly prohibitive. Linking of resources within a supply-chain and industry is believed to be required to effectively overcome the barriers for initial development and qualification of new alloys for aero engines.

General Electric and Pratt and Whitney jointly developed a new turbine engine disk alloy, called ME3, as part of a nearly $200M Enabling Propulsion Materials (EPM) program sponsored by NASA. [3] This material was developed to meet the requirements of two engine OEMs and has been awarded a patent owned by NASA and these OEMs. [4]

An even more successful collaborative effort to develop a new nickel-base superalloy for turbine engine applications has been the development and qualification of Allvac-718plus through the Metals Affordability Initiative (MAI) consortium. [5] The U.S. Air Force, OEMs, material suppliers and component producers came together to develop a common requirements document (specification outline) for a new turbine engine case alloy that would have high temperature capabilities and properties like Waspaloy, but would be more manufactureable, weldable and have a cost structure more like Alloy-718. The new alloy was assessed along with a number of other alloys and was down-selected as a material to further develop and jointly exploit for future applications by the OEMs. [6] A common industrial specification was created, making this material accessible to the entire aerospace industry. [7] The issues of funding for initial alloy development, alloys screening, scale up and demonstration were overcome through collaborative efforts and companies jointly leveraging government funding. Additionally, the potential volume for this material will enable reduced alloy costs through volume production, which supports the goal of all companies involved.

Future alloy development efforts will most likely be based on similar collaborative efforts. One large change, however, will be seen as alloy development continues. Further application of Alloys-by-Design [8] and Materials-by-Design [9] approaches will be utilized. Computational tools have developed to the point where alloy optimization can be assessed virtually through greater understanding of physics-based alloy capability/limitation drivers. CALPHAD predictive tools have been used to support material and process designs for Alloy-718 [10] and Allvac-718plus [11]. Many additional materials models are being developed and utilized to assess issues of castability, grain structure controllability, defect generation potential and mechanical property capabilities. Recent efforts to develop advanced steel alloys [9] and nickel-base superalloy airfoil alloys [12] have shown significant cost and time to develop new alloys.

Computational approaches to alloy design are based on utilization of physics-based models that are linked together within an optimization process to develop the most proper balance of properties, such as cost, mechanical properties, manufacturability and oxidation capabilities for example. Designer inputs from a component and system level standpoint are needed to select the most important attributes for a new material and to enable ranking of their level of importance. Optimization of alloys within a multiple-characteristic space is complex, since many desired characteristics are mutually exclusive.

In addition to new alloy development through the use of computational tools, existing alloys are now being and will continue to be further optimized for specific component applications. Figure 4 shows an example disk where the mechanical properties are predicted for use in location-specific design processes. The alloy chemistries may not be altered, but the local processing of materials is being defined to produce unique component location-specific properties. This can be accomplished in the form of dual- or graded-microstructure components. Figure 5 shows an example of a dual-microstructure disk that has optimized properties at each specific location within the disk volume.

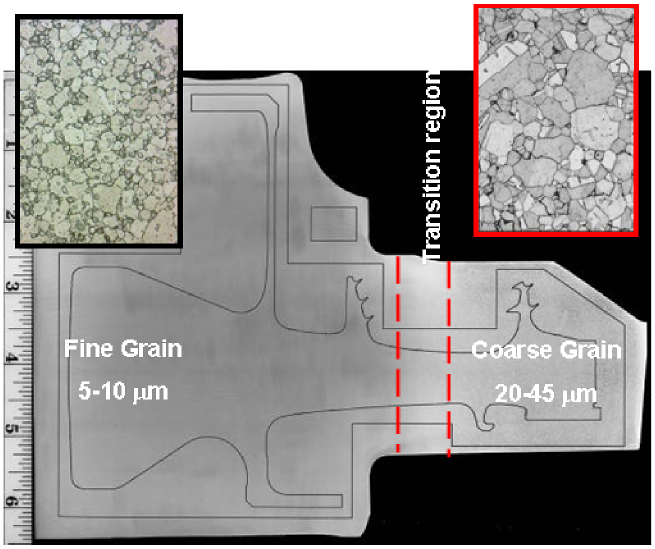

Figure 4. Example of predicted mechanical properties for an advanced turbine engine disk designed from a legacy alloy where the location-specific mechanical properties can be utilized for design optimization.

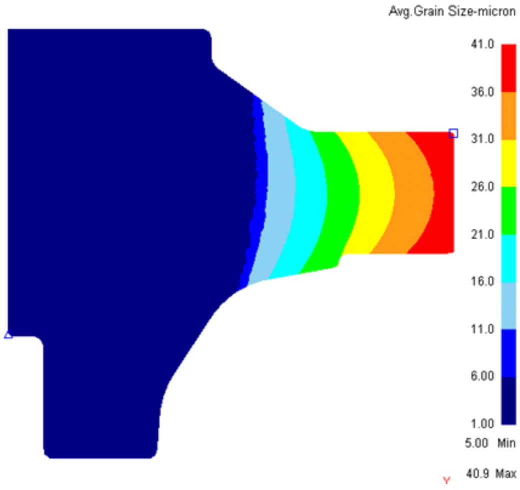

Figure 5. Predicted grain structure for an advanced hybrid disk produced from RR1000 nickel-base superalloy. The engineered local microstructures produce the desired optimum mechanical properties to fulfill the requirements for the disk and overall system.

Existing alloys can often exhibit a different balance of mechanical properties when processed to different sets of microstructures (e.g. grain sizes and precipitate sizes). The development and application of a physics-based model within the component and manufacturing process development sequence enables capture of further capabilities from existing alloys.

Integrated computational materials engineering (ICME) will be a significant part of future alloy design efforts. [13] ICME tools and methods will provide increased understanding of notional alloys and will reduce risk from rapid scale up and application into full-scale components. These tools will also enable optimum utilization of new and existing alloys through location-specific design methods.

In addition to the major costs of alloy screening, scale up, database development, specification generation and deployment, the certification and qualification of new alloys for aero engines is a major hurdle that can halt the deployment of a new material. ICME tools can support assessment of alloy and process variability and can provide a physics-based approach to risk assessment as opposed to entirely phenomenologically-based methods, where large volumes of material (ingots, billets, castings, forgings, heats, etc) are required to be produced in order to develop an understanding of variability and material capabilities.

Though the barriers for new alloy development are high, collaborative efforts along with new computational tools will support further alloy development and deployment for special applications and requirements. Reducing the risk to each organization by sharing the costs and assessment efforts as wells as by employing physics-based modeling and simulation tools will enable the next generation of advanced alloys to be developed in reduced time. The aerospace materials community needs to catch up to the speed of systems development, qualification and certification; collaboration and computational methods are the way forward.

Conclusions

There are a number of barriers inhibiting the development and introduction of new alloys into aero engines. These have been overcome in the past by various means, but often at great expense and over very long time scales. The barriers for new alloy development include:

1. High alloy development costs
2. Risks associated with scale up and material capability uncertainty
3. Risks of alloy capability robustness leading to high costs for qualification
4. Potential need for strategic, low-availability alloying elements

There are specific approaches that can lower these barriers for new alloy development and utilization. These approaches include:

1. Focused and concerted collaborative alloy design efforts to maximize company and government funding available for alloy development efforts
2. Application of ICME tools to support virtual alloy design
3. Application of ICME tools and probabilistic methods to support reduced time/cost for alloy qualification

References

1. J.L. Bartos, "Review of Superalloy Powder Metallurgy Processing for Aircraft Gas Turbine Applications", MICON 78, ASTM, pp. 564-577.

2. E.S. Huron, et. al., “Development of High Temperature Capacity P/M Disk Superalloys”, Superalloys 2008, R.C. Reed, et. al. editors, TMS, 2008, pp. 181-189.

3. F. Preli, Aeromat 2010, Plenary Presentation, ASM-International, June, 2010.

4. U.S. Patent 6,521,175, February 18, 2003; “Superalloy optimized for high-temperature performance in high-pressure turbine disks”.

5. T. Bayha, D. Evans, D. Furrer and A. Poole, “Metals Affordability Initiative Consortium”, Advanced Materials and Processes, May, 2002, pp. 30-32.

6. U.S. Patent 6730264 B2, 04 May 2004; "Nickel-Base Alloy" (Allvac® 718Plus® Alloy).

7. ASM Specification 5442, Society of Automotive Engineers, 2006.

8. R. Reed, T. Tao, N. Warnken, “Alloys-by-Design: Application to nickel-based single crystal superalloys”, Acta Materialia, Vol. 57, Issue 19, PP 5898-5913, 2009.

9. C. J. Kuehmann* and G. B. Olson, “Computational materials design and engineering” Materials Science and Technology 2009 Vol. 25 No. 4, pp. 472-478.

10. K. Wu, F. Zhang, S. Chen, W. Cao and Y. A. Chang, “A Modeling Tool for the Precipitation Simulations of Superalloys during Heat Treatments”, Superalloys 2008, eds., R.C. Reed, K. A. Green, P. Caron, T. P. Gabb, M. G. Fahrmann, E. S. Huron, S. A. Woodard, TMS, 2008, pp 933-939.

11. X. Liu, et. al., “Fatigue Propogation Behaviors of New Developed Allvac 718plus Superalloy”, Supealloys 2004, K.A. Green, et.al., editors, TMS, 2004, pp. 283-290.

12. C. Rae, “Alloys by Design: modeling next generation superalloys, Materials Science and Technology, Vol. 25, Number 4, pp. 479-487, 2009.

13. Integrated Computational Material Engineering – A Transformational Discipline for Improved Competitiveness and National Security, National Academies Press, 2008.