

## Superalloy Technology—A Perspective on Critical Innovations for Turbine Engines

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**Keywords:** high temperature structural materials, nickel-based superalloys, aero-propulsion, vacuum arc melting, investment casting, forging, materials modeling

**Abstract:** High temperature structural materials, such as nickel-based superalloys, have contributed immensely to societal benefit. These materials provide the backbone for many applications within key industries that include chemical and metallurgical processing, oil and gas extraction and refining, energy generation, and aerospace propulsion. Within this broad application space, the best known challenges tackled by these materials have arisen from the demand for large, efficient land-based power turbines and light-weight, highly durable aeronautical jet engines. So impressive has the success of these materials been that some have described the last half of the 20<sup>th</sup> century as the Superalloy Age. Many challenges, technical and otherwise, were overcome to achieve successful applications. This paper highlights some of the key developments in nickel superalloy technology, principally from the perspective of aeronautical applications. In the past, it was not unusual for development programs to stretch out 10 to 20 years as the materials technology was developed, followed by the development of engineering practice, and lengthy production scale-up. And many developments fell by the wayside. Today, there continue to be many demands for improved high temperature materials. New classes of materials, such as intermetallics and ceramic materials, are challenging superalloys for key applications, given the conventional wisdom that superalloys are reaching their natural entitlement level. Therefore, multiple driving forces are converging that motivate improvements in the superalloy development process. This paper concludes with a description of a new development paradigm that emphasizes creativity, development speed, and customer value that can provide superalloys that meet new needs.

### Introduction

The modern world has made great use of high strength structural materials to design facilities and equipment that we cannot live without. Structural materials are the backbone of any mechanical system since they must support the loads and endure the degradation modes of the operating environment. The critical roles played by materials that reliably serve under difficult conditions is impressive. For example, electric generating plants, oil refineries, chemical processing plants, industrial furnaces, and aircraft engines all depend on nickel-based superalloys. Our industrial age could hardly exist without the capabilities enabled by these materials. But the public is generally not aware of these materials since they are specialized and oftentimes are not directly observed.

The aviation industry, with its current fleet of airplanes powered by fast, fuel efficient, quiet engines, would not be possible without superalloys. Jet engines are particularly challenging for structural materials since the operating environment is hot, loads are high to minimize weight, stiffness is crucial to maintain clearances throughout the operating envelope, critical structural components are buried deep within the engine and not easily accessible for inspection and repair, and the expectation is that the engine will operate for 30 years, or more, safely carrying passengers and cargo. Imagine how different our society would be if people could not travel quickly and inexpensively to any destination throughout the world. In a real sense, jet travel is one of the

hallmarks of our modern age since its invention in the late 1920s. And the long-term demand for travel by airplane continues to grow, spurred on by its affordability for the average family in countries throughout the world. Another key reason for this growth is that travel by air has become exceedingly safe: the probability of life lost, or injury, during air travel is considerably less than that of highway travel, for example.

### Overview of Jet Engine Fundamentals

In order to understand the application of superalloys to jet engines, a fundamental understanding of engine operation is useful. Basically, jet propulsion is that propelling force generated in the direction opposite to the flow of a pressurized mass of gas that exits through the jet nozzle. Thus a modern jet engine combines the principles of a simple water wheel with that of garden hose nozzle, except that gas rather than water generates the propulsive force.

For the typical turbofan jet engine (Figure 1), air is continuously drawn into the engine inlet and pressurized by a large fan. This pressurized air exiting the fan either flows directly back into the atmosphere through a propulsive nozzle to provide thrust, or flows into the jet engine “core”. In the core, a compressor further boosts the air pressure, a combustor mixes in fuel and burns it at constant pressure, and the hot gas is expanded through a high pressure turbine which provides energy to drive the compressor. The gas exiting the high pressure turbine then further expands through a second low pressure turbine which, in turn, drives the front fan. The core air exiting the low pressure turbine flows through a propulsive nozzle providing additional engine thrust.

The fraction of fan air which flows around the engine core versus that portion which flows into the core is called the “bypass ratio”. The higher this ratio, the more fuel efficient the engine. Thus, most large commercial aircraft, have engines with bypass ratios on the order of 4:1 to 8:1. Figure 2 shows a cut-away view of a modern high bypass ratio turbofan engine.

From a thermodynamic perspective, the engine can be modeled as a Brayton heat engine. High thermodynamic efficiency requires high operating temperatures to improve turbine efficiency and achieve higher power levels. Thus there has been a relentless quest for more capable materials in advancing jet engine technology.

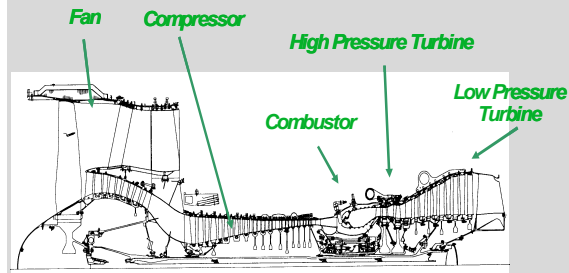


Fig 1: Three Dimensional Cross-Section of a High Bypass Jet Engine

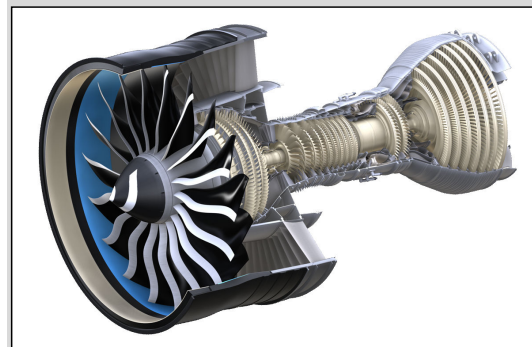


Fig. 2: Three Dimensional Cut-Away of a High Bypass Jet Engine

**Early jet engine materials.** The first jet engines necessarily relied on steels, especially the stainless steels, for hot-section components, as these were the only strong heat resistant alloys available. The temperature limitations and weight of these materials led many to forecast that jet engines for powered flight would never be practical.

The search for alloys with greater high-temperature strength (such as creep) started in Europe with the development of the Nimonic alloy series in Great Britain and the Tinidur alloys in Germany. Within the United States, the Inconel series alloys were originally developed to provide

high creep strength materials for exhaust-driven superchargers for piston engines. These early alloy families and their derivatives have formed the basis for the materials revolution that has sustained the industry for more than 60 years. Achieving a suitable property balance has been difficult and has required significant processing advancements, as well as the more widely appreciated alloy development.

The term superalloy refers to a class of nickel and cobalt based alloys specifically designed for use under conditions of high temperature. Superalloys alloys are “super” because they possess outstanding strength (tensile, creep and fatigue strength) and excellent ductility and toughness at elevated temperatures (above 0.50 solidus temperature, and up to ~0.75 of the solidus) that no other metallic system has been able to match.

During the 1950s, materials available for gas turbine engines were much improved in temperature capability through chemistry changes (alloy development) and melting improvements. The initial alloys used were primarily existing, prosaic solid solution strengthened alloys; they were in effect derivatives of oxidation resistant ground-based turbine rotor stainless steels adapted for aggressive conditions, such as high temperature oxidation and corrosive environments.

The addition of small amounts of titanium and aluminum (two reactive elements) to nickel alloys were a crucial development: an intermetallic phase ( $\text{Ni}_3\text{Al}$ ), known as gamma-prime ( $\gamma'$ ) was precipitated. Gamma-prime is a highly effective strengthener that is extremely stable at high temperatures. At the time of its discovery,  $\gamma'$  in its coherent lattice form could not be resolved by the then current metallography equipment, but its existence was uncannily inferred by materials scientists—this truly ranks as one of the great discoveries of the 20<sup>th</sup> century. Indeed, the U.S. National Academy of Engineering highlighted *High Performance Materials* is as one of the top engineering accomplishments of the 20<sup>th</sup> century. [2]

### Differences Between Commercial and Military Jet Engines

Considering the application regime, military fighter engines continually push the performance envelope in every respect, such as high power, quick take-offs, high maneuver loads, and large excursions in engine speed imposed by combat conditions. In contrast, commercial gas turbines operate at lower take-off power settings, and do not experience rapid acceleration maneuvers. Commercial engines operate for long periods at modest thrust settings.

Consequently, military engines make severe demands on structural materials, and require more inspections and maintenance than do commercial engines. Indeed, commercial engines stay on-wing (i.e., not require maintenance that removes them from the aircraft) for much longer periods of time than military engines. These maintenance intervals are determined by the number of thermal excursion cycles (for components limited by low cycle fatigue) and/or operating time (for components limited by creep). The considerably longer expected time on wing for commercial engines versus the more severe mission profile and operating environment for military systems can result in different material selection for similar components between these engine classes.

The commonalties of minimum weight designs, minimization of fuel burned, and stringent man-rated reliability requirements apply to both mission profiles; more often than not, these overarching commonalties plus the cost/benefit of dual use materials, drive alloy commonality between military and commercial systems.[1]

Military fighter engines achieve higher thrust-to-weight ratios than transport engines by using an augmentor, also known as an after-burner. The augmentor is essentially part of the exhaust nozzle—fuel is injected into the augmentor air stream, where it is ignited to produce additional thrust. This boost can amount to as much as a 50% increase in thrust. The augmentor nozzle also contains movable flaps and seals that create a variable nozzle area, which provides additional control of thrust output.

### Further Superalloy Development

By the late 1950's, turbine engine developers were becoming limited by the mechanical and temperature constraints of the stainless steels. Superalloys were soon targeted for rotating structure components, such as turbine disks and turbine blades, and static structure components, such as pressure cases and frames. But superalloys were not quickly adopted because of fabrication difficulties, such as cracking during forging and strain-age cracking during post-weld heat treatment.

Driven by the national commitment to Aerospace in the United States, significant funding was made available to universities, and government and industrial laboratories, for alloy and process development. Superalloy producers forecast large market growth arising from a number of sources: advanced military aircraft, a growing commercial aircraft market, and the national commitment to space systems. Consequently alloys emerged from laboratories at an unprecedented pace. The sequence of discoveries of the effects of key alloying element additions and the development of useful heat treatments were intertwined and often occurred independently in different locations. Progress in new alloys was rapid, but also chaotic and undisciplined, and oftentimes done under the cloak of "company proprietary" research and development.

Significant alloying and process improvements were made on the  $\gamma'$ -strengthened nickel-based systems; new alloys were stronger at all temperatures of interest than predecessor alloys and were capable of pushing the temperature envelope for applications. In a parallel, progress was made on the gamma-double-prime ( $\gamma''$ ,  $\text{Ni}_3\text{Nb}$ ) strengthened iron-nickel base alloys. These alloys were exemplified by alloy IN718. While not having quite the temperature capability of their  $\gamma'$  cousins, the  $\gamma''$  alloys possess high tensile strength and are more easily processed and welded. The sensitivity of early  $\gamma''$  alloys to notch failure in creep rupture tests was readily corrected via improvements in melt processing and sulfur control. IN718 quickly found adherents within the propulsion industry due to its excellent balance of properties, reasonable cost, and its castability, forgeability, and weldability. Indeed, more than 50 years after the introduction of IN718, the great majority of jet engines use alloy 718 as the material of choice in applications below approximately 650°C (1200°F). (Note: Alloy 718 has evolved from the first IN718, with chemistry and heat treatment changes to optimize various properties.) Today, there are many variations of alloy 718 in use. Therefore, the development of IN718 was seminal event in enabling modern turbine engines.[3] IN718 is arguably the most successful superalloy to date.

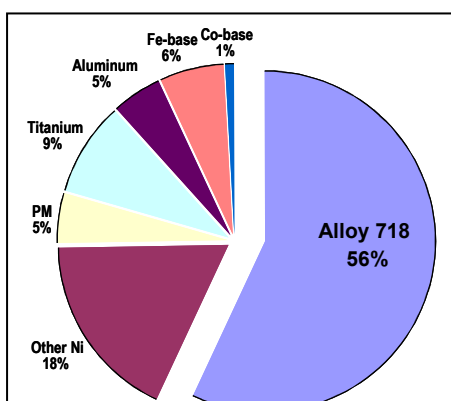


Fig. 3. Metals Used in GE Aviation Engines during 2000

Fig. 3 shows the breakout of metals used in GE Aviation engine forgings in 2000. Note that alloy 718 accounted for well over 50 percent of the total.[4]

Many factors contributed to the evolution of today's alloys. Some of the significant discoveries that have guided superalloy evolution include:

- Excessive alloying additions were found to result in precipitate phase instability manifested by the gradual formation of topological close packed (TCP) intermetallic compounds. The result is that the alloy becomes embrittled during service exposure by the acicular shape of the TCP phases, usually in the grain boundaries, that effectively act as notches, and by the depletion of key elements from the matrix. Obviously, the breath of alloy development is significantly

constrained by this phenomenon.

- It was discovered that slow precipitation, during service life, of phases considered non-embrittling, such as carbides, actually degraded alloy strength. Therefore, carbide stability within the application temperature window is a key consideration.

- To allow heat treatment of most wrought alloys and many cast alloys for mechanical property control, a meaningful difference (at least 30°C, or 50°F) between the hardening precipitate phase solvus (dissolution) temperature and the alloy melting point is necessary. This permits re-solutioning and re-precipitation of strengthening phases. This criterion effectively limits the quantity of strengthening elements that can be added to the matrix since highly alloyed metals tend to have little temperature separation between the liquidus and solidus temperatures.
- Alloys can be tailored to optimize performance for specific environments, such as improved oxidation or sulfidation resistance. However, this tailoring causes a reduction in other mechanical and/or physical properties.
- Alloy compositions possessing the most desirable properties for each application were not always producible in the design-required configuration due to inherent processing and formability limitations.
- As more strengthening elements were added, the ductility of the resultant alloys was concomitantly reduced. A major barrier was found at the minimum ductility point for turbine airfoil alloys, usually between 650°C and 760°C (1200°F and 1400°F). This problem was manifested by the creep rupture failure of turbine blade attachments. This problem also led to strain-induced cracking of turbine airfoils during casting solidification and/or heat treatment. This problem was addressed 3 ways:
  - (a) Engineers adopted a design rule that required airfoil alloys to have at least 2 percent ductility at 760°C. This limited the use of certain high creep strength alloys, but was necessary to protect from the possibility of structural failure.
  - (b) It was discovered that the addition of a small amount of hafnium led to an acceptable minimum ductility level for most alloys.
  - (c) Eventually the grain boundary ductility shortfall in high strength blade alloys was solved by an unexpected processing breakthrough: directional casting solidification that virtually eliminated grain boundaries in the principal stress direction.
- Strengthening of cobalt alloys is only possible by solid solution alloying and carbide distribution. Cobalt alloys therefore lag nickel alloys in breath of application. But cobalt alloys have several advantages over high temperature nickel alloys: higher melting point, and therefore higher use temperature capability; better environmental resistance in certain environments; and better weldability since they are solid solution strengthened. These factors combined to make cobalt advantageous in static part applications that do not require high strength.

### Environmental Resistant Coatings

The progress made in alloy development (and casting technology) provided significant improvement in turbine blade performance. Continued increases in turbine temperature resulted in mechanical and physical property imbalance when it became apparent that the environmental resistance of highly capable turbine airfoils alloys did not possess necessary durability. This was attributable to several factors. First, the intrinsic environmental resistance of the alloys naturally decays with escalation in operating temperature; second, the alloying elements that impart creep resistance often compromise environmental properties; and third, elements that provide environmental resistance perversely encourage the formation of brittle TCPs.

Hence as alloy compositions continued to achieve greater high temperature strength, environmental degradation of uncoated airfoil surfaces, including internal cooling passages, became a leading concern regarding deterioration and maintenance cost. Thus improvements in coating technology were required to allow the alloy benefits to be fully exploited.

In response to this need, oxidation resistant coatings were developed and applied to airfoils to improve environmental resistance. Initial coatings were “pack” coatings, which diffuse aluminum into an airfoil surface, forming an adherent and oxidation resistant layer of NiAl, typically 0.08μm

to 0.13 $\mu\text{m}$  (3 to 5 mils) in thickness. However this improvement in oxidation resistance caused a loss of surface ductility due to the inherent coating brittleness. Design engineers learned to adjust their design practices to accommodate this fatigue penalty.

Production methods were developed to apply an aluminide coating by gaseous phase transport to coat internal surfaces. Importantly, process engineers devised methods of masking the highly loaded areas that should not be coated, such as dovetail attachments, thereby preventing premature fatigue failure in highly stressed regions.

As metal surface temperatures continued to unrelentingly increase, further mitigation strategies were necessary. Pure aluminide coatings were unable to sustain oxidation resistance at these higher temperatures. In response, a superior, but more costly, family of coatings was founded and implemented. These "overlay" coatings were highly oxidation resistant alloys containing chromium, aluminum and yttrium plus solid solution strengtheners, such as cobalt and/or nickel. In line with their elemental composition, they were designated MCrAlY (cobalt and nickel comprise the "M"). They were applied by several different methods, such as plasma spray, electron beam vapor deposition and sputtering. Often, these coatings were used in conjunction with diffusion coatings to achieve enhanced resistance to deterioration by spalling.

The growth of coating technology occurred somewhat autonomously from high temperature alloy design. What began serendipitously, in hindsight, soon became critical, as coating technology became essential to the maturation of high temperature airfoil designs. Coated blades, with the aid of film cooling, were now capable of operating at local temperatures close to the incipient melting point of the alloy, and at bulk temperatures nearing the hardening phase (gamma prime) dissolution temperature. Further hot section airfoil temperature advancements demanded a new concept to gain further capability without employing even more cooling air.

The maximum gas temperature within a jet engine generally occurs during a transient condition, e.g. commercial aircraft only attain maximum temperatures at take-off. Consequently, a means for protecting the metal during these transients would allow reduction in cooling air requirements. Fortuitously, certain ceramics have thermal insulating capabilities that are suitable for this transitory condition. However, the concept of applying a ceramic thermal barrier coating (TBC) was not without challenges. One concern was that a ceramic material would not adhere to the metallic substrate, particularly after repeated thermal cycling, since the coefficients of thermal expansion of the coating and the substrate are very different; this thermal strain would have to be accommodated. Another concern was that the brittle ceramic layer would reduce fatigue life of the airfoil. Prior experience of using TBCs on static components, notably combustion liners, and the knowledge that analytical methods could be developed to deal with nil ductility coatings, suggested that success was possible.

TBC's, based on yttria-stabilized zirconia were successfully developed and applied to airfoils in thin layers, typically 0.13 $\mu\text{m}$  to 0.25 $\mu\text{m}$  (5 to 10 mils) thickness. Conventional coating processes, such as plasma spray and physical vapor deposition (PVD) were suitable for depositing high quality, thin ceramic layers. The deposition process was further refined to avoid depositing TBC's in local areas through direct masking, or virtual masking; i.e., manipulation of the component holding device during the coating sequence and to allow depositing variable thicknesses at selected locations.

Fortuitously, the metallic oxidation-resistant coatings that were applied directly to the surface of the superalloy to improve environmental resistance, also served as an intermediary layer for bonding the ceramic to superalloys.

### **Current Superalloy R&D Directions**

**New Age Hardenable High Temperature Nickel Alloy.** IN718 (now conventionally referred to as alloy 718) has been immensely successful since it has an excellent balance of mechanical strength, phase stability, and processability. A number of improvements have been made over the years to alloy 718 in melting, ingot conversion, forging, and heat treatment.

The gamma-prime-strengthened alloys typically are stronger but much less processable. However, engine designers have been relentlessly increasing engine temperatures. The metastability of the gamma-double-prime phase in alloy 718 above 650°C (1200°F) has been the key limitation on its application. This has dictated the selection of gamma-prime alloys for applications that are hotter than 650°C. However, these class of alloys, such as René 41 and Waspaloy, pose significant component manufacturing challenges since they are not very weldable or easily formable, and are prone to strain-induced cracking. Therefore, a long-standing need has been an alloy with the slow precipitation kinetics of Alloy 718 that retains properties with up to 50°C (nominally 100°F ) greater temperature capability.[5]

Since the introduction of alloy 718, numerous alloy chemistries have attempted to match the favorable processability of alloy 718 with increased thermal stability to higher temperatures. A recent alloy, known as 718Plus<sup>®</sup>, has shown phase stability sufficient for operating temperatures of 704°C for many applications. (718Plus<sup>®</sup> is a trademark of ATI Allvac.) 718Plus material is a derivative of alloy 718, with the major change being the addition of 9 weight percent cobalt, reduction of 8 percent iron, Al/Ti of 2, Al+Ti of 2.15, and addition of 0.002 percent phosphorus.[6,7] Table 1 compares the chemistry of the 718Plus material to alloy 718 and to Waspaloy.

Table 1. Nominal Chemistries of Selected Superalloys (weight percent)

Alloy	Ni	Cr	Mo	W	Co	Fe	Nb	Ti	Al
718	Bal.	18.1	2.9	-	-	18	5.4	1	0.45
718Plus	Bal.	18	2.8	1	9	10	5.4	0.7	1.45
Waspaloy	Bal.	19.4	4.25	-	13.25	-	-	3	1.3

The Allvac development program included both computer modeling and experimental melting trials. The modeling work was useful in analyzing the optimum Al/Ti and Al + Ti levels. Key to success of the alloy is its sluggish precipitation of gamma-prime, which is thought to be due to the high niobium content in the gamma-prime phase.

An important aspect of this program is that it was selected for scale-up demonstration in non-rotating components under a US Air Force program, Metals Affordability Initiative, which included engine manufacturers (General Electric, Honeywell, and Pratt & Whitney), forgers (Firth-Rixon and Ladish Co), primary metal producers (Allvac and Carpenter Technology), and the Air Force Research Laboratory. This consortium approach helped insure that the material met market needs, that there was a supply chain capable of producing the material and desired component forms, and provided an effective mechanism to study and report on the understanding of the metallurgy of the new alloy. A collaborative approach is becoming the desired way to conduct such programs to reduce development time and application uncertainty.[8]

**Improved Disk Alloys.** Disks made via the powder metallurgy route have superior properties owing to the better control of elemental segregation and finer grain size than can be achieved via the conventional cast and wrought process. Powder metallurgy disks are not without challenges, however, which include cleanliness and powder handling, consolidation into a defect-free structure, heat treatment that produces desired properties, and added cost of the additional processing steps. Nonetheless, most advanced disks are made via the powder metallurgy route since the overall benefits outweigh the drawbacks.

Work during the 1990's for NASA's High Speed Civil Transport Program, which was aimed at technology for a commercially viable supersonic flight vehicle, identified the need for a disk material that could withstand long dwell fatigue cycles and creep/rupture loading cycles at temperatures above 704°C (1300°F). A new disk material was developed in a consortium comprised of General Electric, Pratt & Whitney, and NASA Glenn Research Center. The alloy was designed to have an improved creep and fatigue resistant microstructure, combined with stronger grain boundaries to handle high disk rim temperatures. To achieve the desired combination of

properties, the resultant superalloy, known as ME3, possesses the requisite temperature properties at 704°C; this was achieved through careful control of the grain boundary chemistry and precipitates, and an optimum super solvus heat treatment that led to maximum performance within the operating conditions of interest. [9,10]

Rolls Royce also developed a new powder disk alloy, RR1000, for a subsonic engine application. They applied past experience, as well as advanced thermodynamic modeling capability to predict phase stability and TCP formation. In order to encourage damage tolerance, this disk was designed to have a minimum volume fraction of  $\gamma'$  phase consistent with attaining the desired strength level. The levels of Al, Cr, and Mo are within the range that was predicted to avoid TCP formation. Near-solvus heat treatment and fan air-cooling of the forged material provide an acceptable balance between tensile strength and damage tolerance.[11]

**Next Generation Airfoil Materials.** The development of a new airfoil alloy for the supersonic application was also undertaken by the General Electric, Pratt & Whitney, and NASA Glenn Research Center consortium for the High Speed Civil Transport Program. Subsonic engines accumulate hundreds of hot time hours, while supersonic engines accumulate thousands of such hours. Therefore key goals of the program included microstructural stability to avoid degradation of long-time properties, acceptable environmental resistance, and good castability and producibility. Obtaining that balance of properties was challenging. In addition, the alloy had to avoid secondary reaction zone (SRZ) instability that can develop beneath PtAl and MCrAlY coatings, and avoid the formation of topologically closed packed phases. Reactive elements, Hf, Y, Ca, were key to improving oxidation resistance. High creep-rupture required an increase in refractory element content (Mo, W, Ta, Re). But achieving all of the requirements would not have been possible without the addition of a platinum-group metal, ruthenium (Ru), which was discovered to be critical to promoting microstructure stability. [12]

The High Temperature Materials 21 program, conducted at Japan's National Institute for Materials Science (NIMS) has been developing new single crystal alloys with superior creep strength and microstructural stability, capable of operation in both subsonic and supersonic engine applications. The primary emphasis has been to increase creep rupture strength at the higher temperatures through a combination of data-driven modeling and key experiments to guide the selection suitable chemistries. Using this approach, a number of high temperature airfoil materials have been discovered. [13]

### Process Technology

In parallel with the alloy improvements, and oftentimes leading it, developers made significant improvements in the processes by which superalloy wrought and cast shapes could be produced. The importance of these processing advances to the design of turbine engine components cannot be over-emphasized. For example, weldability improvements in the nickel alloys allowed significant increase in the size and complexity of cast structures by enabling weld repair of casting defects; this allowed manufacture of complex-shaped components, such as frames, using only a few parts, enabling lower component weight and higher reliability.

The synergistic interaction of materials and processes is depicted in Fig. 4. This figure graphically demonstrates that each spiral of improvement contains both processing innovations and material improvements for the entire suite of materials used in jet engines.

Materials processing requires invention, arduous process development, and large capital investment. Thus it is often on the critical path for materials development and scale-up.

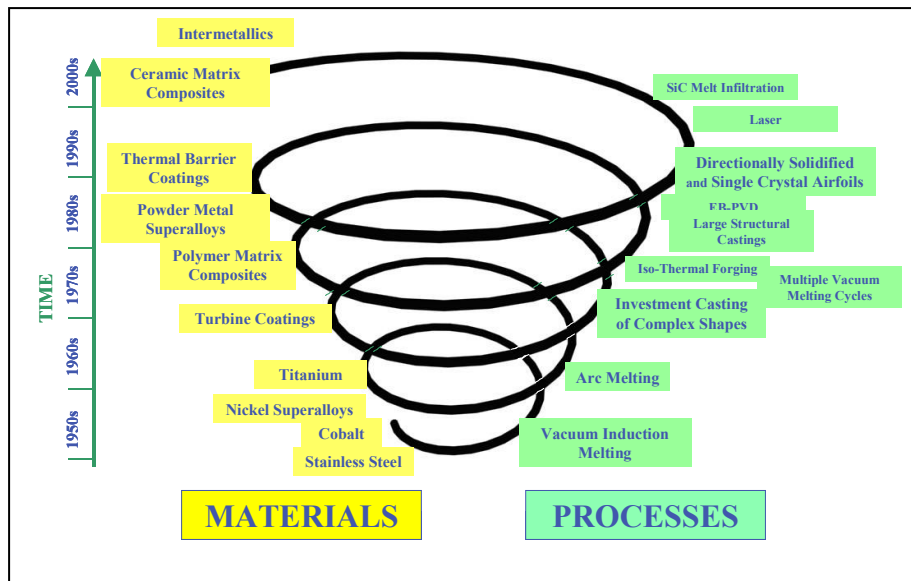


Fig. 4. Synergistic Interaction of Materials and Processes

### Vacuum melting technology.

Advances in propulsion materials technology can arguably trace its roots to the point when vacuum induction melting (VIM) became commercially feasible, about 1950. Prior to this, materials researchers had recognized that vacuum melting increased elemental (and alloy) purity and that certain properties were improved by purity enhancement. During the 1950s, commercial vacuum pumps became available that sustained a vacuum level of  $10\mu\text{m}$  gas pressure, and vacuum sealing technology advanced so that leakage rates into the vacuum furnace could be minimized and managed.

VIM process evolution permitted the elimination of detrimental trace and minor elements in concert with the addition of reactive elements such as aluminum and titanium, without the risk of these becoming oxide inclusions. This was truly a fundamental breakthrough for producing high strength superalloys, since reduction in trace elements increased component reliability, and the addition of reactive elements enabled precipitation strengthening of these alloys.

One of the first "clean metals" produced by VIM was AISI 52100 grade steel, a vintage bearing steel that was adopted in early jet engine main shaft bearings. Bearing steels for flight-rated jet engines had been made in an air-melt electric furnace, and consequently steel properties varied widely due to the presence of multiple oxide inclusions. Bearing failures were common and had serious consequences, such as an in-flight shutdown of the engine.

Bearing steels prepared by VIM were much cleaner than electric furnace steel, and VIM processed steels rapidly became the preferred bearing steel. But these bearings surprisingly suffered from rarely occurring, early failures in a few bearings. The source of the failures was found to be randomly distributed exogenous ceramic inclusions that originated from erosion of the VIM furnace liner, weir, and gating. Thus, VIM successfully removed indigenous inclusions, but the bearings suffered the problem of rarely-occurring exogenous inclusions that caused infant mortality in a small percentage of bearings.

**Vacuum Arc Melting (VAR).** Arc melting in air was first disclosed as a process for the melting of metals in 1839. However, it was not widely practiced for the commercial production of structural materials until after WWII, when vacuum technology became commercially available. Consumable arc melting became a process that followed VIM for superalloys, because alloy formulation and unique chemistry control is best achieved by VIM. VAR ingots in general have

better homogenization and higher bulk density than VIM ingots due to greater control of the solidification rate.

In the case of AISI 52100 bearing steel, a VAR cycle following alloy synthesis by VIM dispersed the exogenous inclusions, and consequently eliminated infant mortality failures. Thus, premium quality bearings are double vacuum melted (VIM-VAR) to the present time.

**Premium Quality Melting.** Superalloy premium quality practices have continued to evolve. Premium quality (PQ) melting requires at least double vacuum melting, and some critical applications require triple melting. The triple melt sequence results in very clean premium quality material with minimal lot-to-lot variation, and therefore material with highly reproducible mechanical properties and processability response.

In modern melt practice, VIM is the production option for the initial heat formulation to establish alloy chemistry. Additional secondary refining is required, however, to satisfy stringent cleanliness and homogeneity requirements. Defects introduced in VIM include non-metallic inclusions, alloy segregation, and shrinkage cavity formation.

Electro-slag re-melting (ESR), a consumable electrode process, uses a controlled composition slag to remove non-metallic inclusions while maintaining control of alloy chemistry. It is often used as the second melting step for PQ material. ESR produces sound, improved cleanliness ingots, but they can be prone to solidification segregation.

Therefore, a third melting step is employed for the most critical applications. Since VAR is effective in establishing a reproducible macrostructure, and does not introduce defects if close attention is paid to process details, it is usually reserved for the final melt step.

**Investment Casting.** Early turbine airfoils were produced from wrought alloys; the first application of a casting for a rotating superalloy component occurred in the 1950s when a solid (i.e., non-cooled) turbine airfoil was investment cast. This event required improved processes to reduce casting defects that limited strength. The driving forces for casting airfoils included increased complexity in the design of airfoils to accommodate internal cooling air passages, and the eventual discovery that airfoils could be cast as single crystals, greatly enhancing their creep rupture lives.

Improvements were also occurring for large structural castings, such as engine casings. The primary driving forces were reduced cost and improved reliability through production of a monolithic structure. While large structural castings are not subject to as demanding an environment as airfoils, their large size and complex casting tooling adds unique challenges.

As design technology advanced, the relentless push for ever greater turbine inlet temperature challenged the materials community. A key limitation was the creep strength capability of turbine blades and vanes at higher operating temperatures. Engineering analysis indicated that significant improvement in engine performance would be gained if the turbine blades were cooled by internal conduction and by establishing a thin film of cooler air over the hottest regions of the blade. Since the air would have to be pressurized to pass through the channels and holes, it was necessary to re-direct, or "bleed", a portion of the pressurized air in the compressor to the turbine blades for cooling. Initially, this technology was implemented by drilling internal cooling air passages in turbine blades, at high cost and extended shop cycle time.

Advances in investment casting technology (based upon the ancient "lost wax" process) soon made wrought turbine blades obsolete. Central to this technology was the development of ceramic core materials that could be placed inside the turbine blade casting mold to produce intricate internal cavities; these ceramics had to be strong enough at molten superalloy temperatures to retain shape, yet able to be completely removed after casting without damaging the casting itself. These cores were found to be removable by caustic solutions contained in heated and pressurized autoclaves, and this break-through paced the evolution of "cast-in" cooling passages.

The desire for strong turbine airfoil castings that required little or no subsequent machining, even with elaborate internal cooling passages, was not realized without overcoming challenges

which included alloy stability, ductility compromise and balance of properties between mechanical strength and environmental resistance.

**Directional Solidification.** For most turbine airfoils, the principal stress direction lies in a direction parallel to the airfoil length. Therefore, it was postulated that if the grain boundaries could be aligned with this direction, airfoil life would be greatly enhanced. Spurred by this idea, Ver Snyder and others, began developing the directional solidification (DS) casting process in which the resulting grain boundaries were parallel to the airfoil length. The DS process was implemented as a production process after substantial development effort.

DS airfoils provided an immediate 25°C increase in creep strength; in addition the intermediate temperature ductility was much improved, and thermal fatigue life greatly enhanced. DS also resulted in greater tolerance to local strains and rupture ductility making it practical to inspect airfoils that had been in-service for local evidence of damage accumulation, such as deformation and/or incipient cracking prior to airfoil failure.

The DS process requires longer processing time and greater process control than does conventional (i.e., "equiaxed grain") casting, and is therefore more costly. The irresistible benefits of the technology culminated in widespread acceptance of DS despite its higher cost. DS technology was soon followed by single crystal (SC) airfoil castings, which eliminated high angle grain boundaries altogether, with further improvement in stress rupture life and an increase in allowable blade operating temperature.

The oft-used gas turbine milieu term "forgiveness" implies a characteristic that imparts detectable damage significantly prior to component fracture. DS and SC added a degree of forgiveness to high temperature airfoils, and continue to be a prevention mechanism for catastrophic airfoil failure. In today's modern turbine engine, nearly all the high- pressure turbine airfoils are either directionally solidified or mono-crystals. So compelling is the cost/benefit ratio that the technology is now used in the cost sensitive stationary gas power generators; single crystal castings weighing up to 20kg are commonly produced for these applications.

**Improving Wrought Superalloy Capability.** In the domain of forging technology, several significant innovations have been important. The first was the evolutionary change from open die hammer to closed die press forging. Presses became larger in platen size and capacity, and improved in temperature capability and die closure rate regulation. This new competence translated into the production of large and complicated shape superalloy components, such as highly alloyed turbine disks with diameters exceeding 1m. The benefits of press forging include part-to-part uniformity of properties, allowing for standard heat treatment procedures that minimize component cracking, and reduced residual stress gradient within components that adds to in-service reliability.

A second major innovation was isothermal forging of superalloy powder metallurgy billets. Turbine disk rim temperatures increased as engine design engineers took advantage of improvements in airfoil temperature capability. Alloy developers responded by increasing the strengthening content of conventional disk alloys. However, these materials exhibited increased resistance to deformation and decreased hot ductility; these effects combined to significantly degrade malleability. These alloys could not be forged into even geometrically simplified shapes without strain-induced cracking. Consequently, these new disk alloys that possessed both high creep and tensile strength were disallowed for use.

An original motivation for powder metallurgy was that the rapid cooling rate during powder formation minimized solidification segregation, allowing the complexity of superalloy chemistry to be increased with commensurate improved temperature performance. Moore and Athey found that deformation behavior of very fine grain size superalloys was sometimes superplastic; i.e., large deformations could be achieved with relatively low press forces under the right combination of strain, strain rate, and temperature. This behavior was used to produce disk alloys via the powder metallurgy that could not be produced using conventional ingot metallurgy. Thus the powder

metallurgy route provided composition and processing flexibility for advanced alloys, albeit at the expense of greater processing complexity and cost.

The manufacture of superalloy powders and the consolidation of the powder into fine grained forging billets required additional innovations. These were contributed by a number of companies and research institutions, and included:

- processing techniques to produce clean superalloy powder
- development of a molybdenum-based die material (Moly TZM) strong enough to deform powder billet into complex shapes at 925°C to 1100°C (1700°F to 2000°F) at slow isothermal forging rates
- enclosing the forging press within a vacuum chamber to environmentally shield the molybdenum alloy dies and the piece being shaped
- establishment of controlled slow strain rate (superplastic) forging regimes

**Near Net Shape Manufacturing.** The high cost and long production lead times required to make aerospace quality parts has spurred the search for improved processing methods that are inherently more efficient and faster than the traditional casting, forging, and machining manufacturing steps. A number of such processes are beginning to be used.[14] The inflationary cost of nickel has been an important factor in the search for processes that require much less input material to make a finished part. Many of the superalloy parts in an engine require 8 to 10 pounds of input material for every 1 pound in the finished part. This excess material not only costs a considerable amount, but the cost to remove it is also high.

Additive manufacturing, which can trace its roots to rapid prototyping, has been gaining ground as an alternate processing method. The technology can quickly and economically directly make prototypes of parts without requiring hard tooling or extensive post-processing. Additive manufacturing is a process that produces part features, and entire parts, in a controlled layer-by-layer fashion using various energy sources to melt powder metals. Geometric information contained within a CAD data file guides the energy source in precise patterns over a layer of deposited powder. When the energy beam hits the powder, it fuses them into the solid shape. “Additive freeform manufacturing” and “layered manufacturing” are typical of this family of processes. This technology currently accounts for a relatively small proportion of superalloy component manufacturing, but many potential applications are under evaluation.

Additive manufacturing has challenges that must be met before these methods become accepted as a fully capable, prime manufacturing methods. The technical challenges include greatly increasing speed and material throughput—for instance, it can take a day or more to build-up an average size part. Improvements are also needed in build-envelope size, accuracy, finish, resolution, and detail. More choices of powder materials must be available possessing the requisite cleanliness. A likely path for introduction is combining additive manufacturing with other manufacturing processes. For example, using additive manufacturing to produce lands and bosses on a streamlined engine case can result in significant material savings.

Sprayforming is a near net shape process that allows direct build-up of semi-finished products in one step. [15] In this technique, atomized droplets are sprayed onto a collector, where they fall into a semi-liquid layer, solidify and build-up a preform. It can produce a uniform distribution of fine grains with high density. It does require contamination-free melting of nickel alloys and inert gas atomization to produce droplets of high cleanliness.

Centrifugal spray deposition is a simpler process, but for a limited application. It can be used for the production of superalloy ring-shaped preforms.[16] Liquid metal is poured through a nozzle and directed onto a rapidly rotating disk or cup. At the edge of the disk, the liquid metal is atomized to form a spray that travels outwards and onto the inner surface of a movable substrate where it solidifies to form a ring-shaped preform. An advantage to this process is that the metal spray is produced mechanically, avoiding the need for inert gas atomization, and allowing the process to be operated in vacuum.

## Engineering Design Practices

So far, two key aspects of material development have been highlighted in the context of superalloys: discovering a material composition and microstructure that provides usable properties, and using a processing route that can readily produce the required material in the required product form. There is a third aspect that is critically important: design practices must be in place to allow specification and usage of the material.[17] Within the aerospace engineering community, this consideration is of paramount importance given the top priority accorded to safety of flight. The technologies of life prediction, coupled with reproducible material properties and reliable non-destructive evaluation, have unequivocally been crucial to providing design engineers the confidence to fully exploit the capabilities of jet engine materials. The outstanding safety record and high reliability of aircraft engines can be attributed in part to the ubiquitous role these technologies play in the application of advanced jet engine materials.

**A Crucial Insight.** The importance of the reproducibility of properties cannot be over-emphasized: for instance, service failures of rotating components, such as turbine disks, always cause in-flight shutdowns of the engine. Thus a great deal of engineering and manufacturing attention is devoted to avoiding all causes of these failures.

The problem of exceptionally deleterious defects that appeared with very low frequency, such as the exogenous inclusions in AISI 52100 VIM ingots mentioned above, provided an important lesson learned that still impacts the development of structural materials. Materials will always contain some defects; i.e., departures from the ideal. Fig. 5 notionally maps the frequency of defects versus the consequence that the defect can have on the functionality of a high-integrity structural element. In order to achieve high reliability, the root cause of the defect must be understood and mitigation strategy developed as part of the material development process.

*Zone 1* represents defects that occur sporadically; when the defects are present, they cause negligible harm. Thus some level of these defects can be acceptable without causing loss of material properties. These defects can be accommodated by design practice changes, specification changes, etc. to increase the tolerances to accept a certain level of these defects.

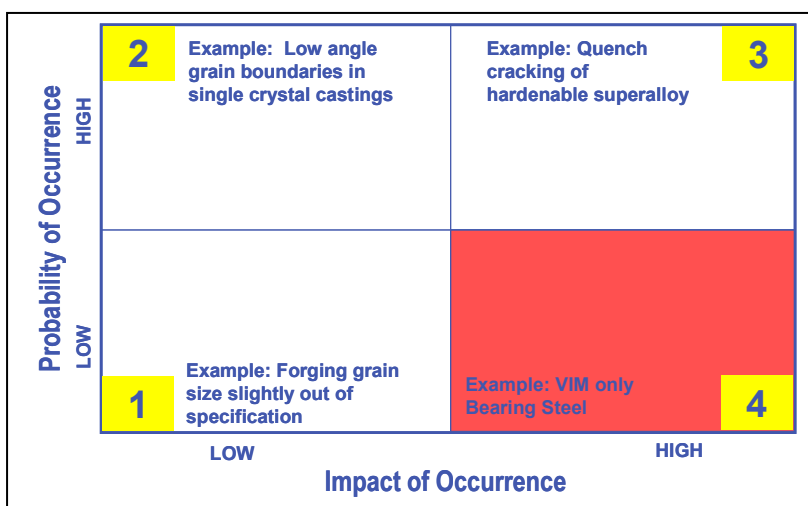


Fig. 5. Risk Assessment Map

*Zone 2* defects occur frequently but cause little detriment. These can be accommodated by design practice changes and specification changes as for *Zone 1*. However, consideration should be given to reducing their frequency by improved process control since the upper limit on acceptable number of defects may not be precisely known.

*Zone 3* defects develop often and are quite deleterious to the performance of the component, such as the example of the AIS52100 air-melt bearing steel.

These defects motivate a nondestructive evaluation (NDE) program. Fortunately, most of the defects that fall into this zone are easily detected. Once these defects are found, the material is typically scrapped or reworked. The frequency of the defects can be reduced through better process control or an improved process once the root cause of the defect is understood.

*Zone 4* is the regime of exceptionally deleterious defects that randomly develop at extremely low frequency, such as one or fewer occurrences per million opportunities. An example of a material in *Zone 4* was the AISI 52100 VIM bearing steel that contained small amount of exogenous oxide inclusions that led to infant mortality of a few percentage of bearings. These defects are usually difficult to eliminate, or minimize, through process changes because they occur so infrequently that determining the benefit of a change requires massive sample sizes over long time spans. Rigorous attention to control at each process step is crucial in preventing the root cause. In the ideal case, an entirely new process would mitigate or avoid the root cause that produced the defect. Heavy reliance on NDE helps to uncover these defects, and remove the defective material from further processing.

**Life Prediction.** Jet engine structural elements are necessarily designed to be as light weight as possible. Engines typically do not have redundant load paths that can carry the load in case one part of the structure fails. Also, engine testing is quite expensive, and in any case, cannot fully simulate 30-40 years of in-service experience. Therefore, engine designers rely extensively on the ability to estimate the life of the different parts in the engine based on knowledge of the material properties, the thermal history the part will experience, knowledge of the underlying degradation mechanisms, mechanical loads, effect of stress concentrating features, etc.

For instance, low cycle fatigue (LCF) is one of the primary failure modes that limits component life within the engine. In most cases, LCF occurs at strain concentrations, such as disk bolt holes and blade retention slots, that are subject to transient loads in excess of the local yield strength even though detectable dimensional change, prohibited by the surrounding mass, does not occur.

A cornerstone of life prediction are baseline material properties that can be assured. Therefore, design engineers do not use the average property values in their analyses: they typically use the properties at the 95 percent confidence level that 99 percent of the data points will be above this minimum value. This approach provides conservatism that is necessary to address the range in properties associated with process variation without compromising design intent.

### **Motivation for Advanced Materials in Jet Engines.**

In aero-propulsion applications, a case can be made for slow adoption of new structural materials since the consequence of making a poor choice can be quite deleterious. Thus the anticipated benefit of a new material, or an existing material that is processed differently to enhance a particular property, must be significant. There are at least three prime driving forces spurring the development of new structural materials, counteracting a conservative “stand pat” management policy.

- Traveling public’s expectation for continued improvement in jet engine safety through higher reliability in mechanical components.
- Competitive pressure for improved engine performance, such as increased thermodynamic efficiency for reduced fuel burn.
- Need for lighter weight structures that allow airlines to carry more passengers and cargo further distances.

A widely used indicator of the technological state of propulsion jet engines is the ratio of engine output thrust to engine weight, the thrust:weight ratio. Whittle's original 840-pound engine generated thrust:weight of approximately 1.5:1 and could operate for a few hundred hours at most. Current commercial jet engines have thrust:weight of 4:1 to 8:1, and advanced engines are targeting higher ratios. These advances are due, in no small measure, to significant improvements in both materials and processes that enabled improved designs.

Using thermodynamic analysis, B. Koff suggested that the inherent efficiency of a turbine engine, compared to the ideal, could be estimated by calculating the power generated by the core of the engine as a function of turbine rotor inlet temperature,  $T_4$ , which is the highest temperature in the engine. Furthermore, Koff pointed out that compressor discharge temperature,  $T_3$ , limits the pressure ratio and hence the flight speed. The result is depicted in Fig. 6.[18] When data from the earliest jet engines through the more recent ones are plotted, it is apparent that engines still have

significant opportunity for improvement to edge closer to ideal efficiency. Since both  $T_3$  and  $T_4$  are constraints, this plot emphasizes the benefits of gains in materials or improved cooling methods to allow further increases in turbine power.

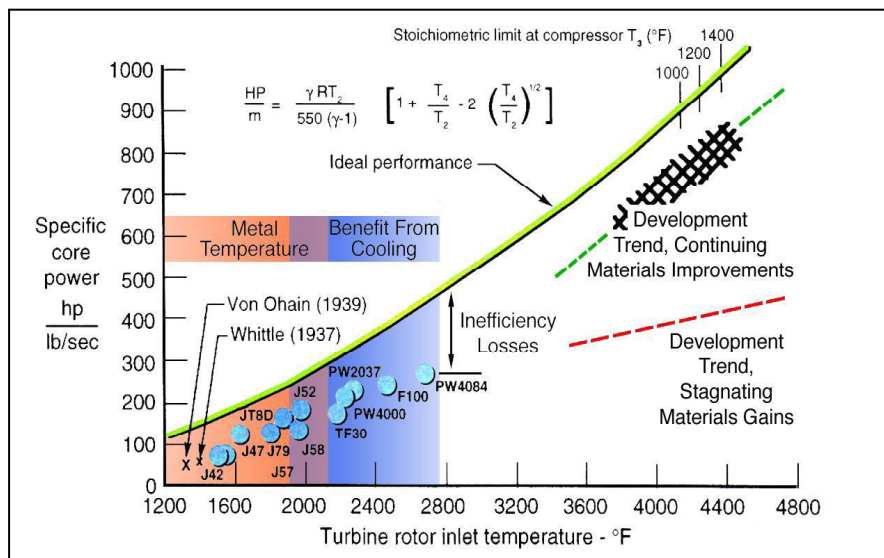


Fig. 6. Turbine Engine Thermodynamic Efficiency

Therefore, considerable advancements still can be made to aero-engines. And materials will necessarily play an important role. But other technologies are also essential: acoustics, aerodynamics, combustion science, design technology, and heat transfer, for example. Engine developers will invest in the development of those technologies that can deliver the greatest benefit. Thus materials and process technologies must compete with these technologies for resources to gain the opportunity to provide improvements.

### A Path to Acceleration Innovation

The historical timeline for material development has been quite lengthy, and was rather constant for some time. However, product development timelines have continued to decrease. Therefore, within the jet engine technology field, materials development has not kept pace. However, there are powerful driving forces motivating the search for better materials and for reduced timelines to incorporate these new materials into critical applications in the engine. The emerging paradigm involves tight linkage between the materials and the engineering design community, using the metric of “customer value” as the guide for selecting technologies.

**Material Development Timeline.** In the past, materials were developed to be “better” than existing materials. The predominate expectation was that design engineers would soon specify the superior material, and applications for the material would be forthcoming. To a large degree, this approach worked. Given the long time required for materials development, design engineers could not accurately foresee what material would be needed in 10 years since they were focused on engineering the next generation engine, not the generation afterwards. And often the materials developers were right in their assessments—they correctly anticipated the need for higher temperature capable superalloys.

Table 2 contains typical times required to fully develop and implement a new material for an aircraft engine application. Very few tools existed to help alloy developers design the chemistry of alloys. (An early exception was the development of models based on Linus Pauling’s Electron Vacancy Theory that provided an estimate of the susceptibility of superalloy chemistries to

deleterious TCP precipitation.) Therefore trial and error, with much testing, was the rule rather than the exception. For instance, General Electric's René 41 superalloy was so named because a usable alloy was discovered on the 41<sup>st</sup> iteration after nearly a decade of research. A new class of structural material, intermetallic TiAl, required 30 years for development.

Table 2. Historical Materials Development Timelines [19]

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Case I. Modification of an existing material for a non-structural critical component
• Approximately 2-3 years
Case II. Modification of an existing material for a critical structural component
• Up to 4 years
Case III. New material within an existing alloy system
• Up to 10 years
-Includes time to define the chemistry and the processing details
-Supply chain already exists
Class IV. New material class with no prior experience
• Up to 20 years, and beyond
-Includes the time to develop design practices that fully exploit the performance of the new material class
-Establish a viable supply chain

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While materials developers continued along this Edisonian path, other disciplines, such as aerodynamics and mechanical engineering, were making strides in computer modeling. Finite element modeling, computational fluid dynamics and heat transfer analysis, to name a few design technologies, were increasingly able to perform design iterations by computer analysis rather than building subscale models and measuring data. For instance, the new composite fan blade shape for the GE90-115B was designed using 3D aero code in 72 iterations over the course of a few weeks. If that work followed the historical materials development paradigm, 72 subscale models would have had to be built and tested in a wind tunnel over the course of several years at great expense. New engine programs are completed within 30 months, aiming toward 24 months. Materials development requires several times this time period.

In essence, design technology has out-paced materials development technology. As design tools become more sophisticated, they demand more material behavior data through-out the temperature range of interest. Typical property data includes: elastic constants, creep and stress rupture, yield and ultimate tensile strength, ductility, strain-rate sensitivity, high cycle and low cycle fatigue behavior, fracture toughness, impact resistance, and crack growth rate. This range of mechanical property data is critical to determining if a given material can satisfactorily perform in a targeted application. Obtaining this data for a new material is often an expensive, lengthily process. Too often materials development efforts have focused on optimizing one of these properties, only to later determine that low performance in another property renders the material unsuitable for the application. Achieving the right balance in properties is essential to identifying suitable candidate high temperature structural materials. Plus, once a new material looks interesting from a design analysis standpoint, further analysis must be done to assess producibility: Knowledge of the phase diagram, recrystallization temperature, machinability, weldability, forgeability, and so on, rise to paramount importance. Consequently, quite a bit of time and effort can be expended to collect all the required data, only to discover that the proposed material solution has serious limitations, is not quite good enough to supplant an existing solution, or is otherwise is not attractive enough for implementation.

**New Material Development Paradigm.** Material developers must rise to the challenge of competition for technology development resources among all the different opportunities to improve

turbine engines. This competition occurs in two levels: materials R&D must compete for funding priority with other technology areas, and various material solutions compete among themselves in a quest for the best alternative. In order to be successful, a materials solution must have a credible “value case” in which the cost of development and implementation is favorably compared with the expected benefit for a given application. Therefore, prioritization of resources requires a credible value case analysis that includes the cost of implementation, which can be considerable for materials technologies, presenting a significant barrier for adoption of new materials and processing technology.

This paradigm is significantly different than the historic approach, which was materials developer centric. This new paradigm is system engineering centric, requiring that proposed materials capability be aligned to design requirements, and critical-to-success metrics identified that can focus resources to assure implementation success.

This process is illustrated in Figure 7. The top portion depicts the stages of technology creation; the bottom half depicts the stages of product creation. For technology creation, the investment is typically on the order of US\$1 million to establish feasibility (Technical Tollgate 3, TTG3), and increases by an order of magnitude to demonstrate capability (TT6), and can increase by another order of magnitude to mature the technology (TTG9) since required supply chain investment costs alone can be on the order of US\$100 million for a new technology if a new supporting industrial base must be established.

Under this new paradigm, materials developers can still exercise a great deal of creativity to establish the feasibility of a new material. A major difference from the previous development regime: feasibility is determined with respect to the needs of a particular component, rather than a generic set of requirements.

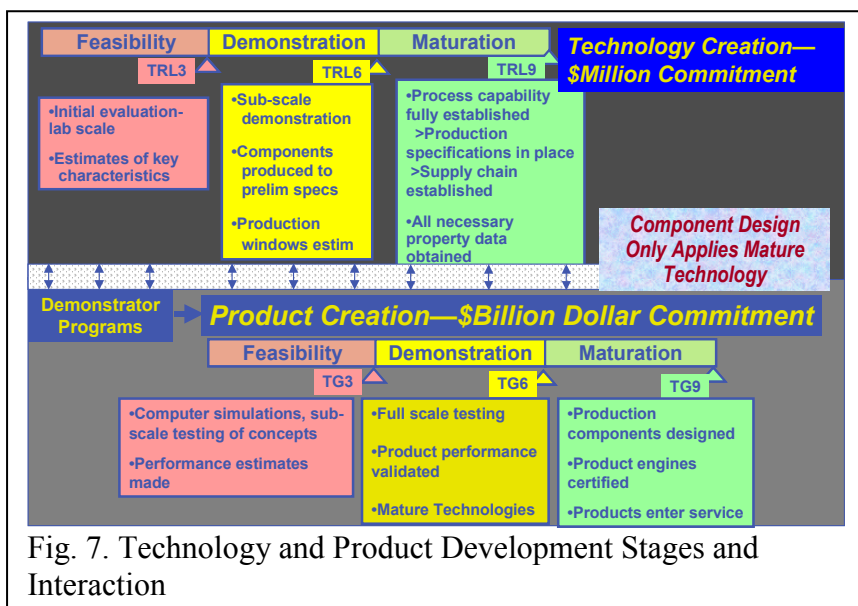


Fig. 7. Technology and Product Development Stages and Interaction

Considering the engine development process, there can be engine demonstrator platforms in operation that prove out various technologies, such as a high efficiency fan, before a formal product creation effort is launched. These platforms explore the realm of the possible, without being constrained to meet specific requirements. Once a decision is made to launch a product however, specific criteria are established that the engine must meet. The product

creation process has 3 key development stages, each of which is defined by a tollgate process that measures progress toward the set of requirements: determine feasibility (Tollgate 3, TG3), demonstrate product capability (TG6), and mature the product for entry into service (TG9). The cost to create a new centerline engine can be US\$1 to \$2 billion, or more, to proceed through to TG9.

Ideally, a technology targeted at an application in the engine will be at TTG9 when the engine development program is at TG6. This allows for the new technology to be inserted into the engine with a minimum of unplanned, costly surprises. Of course, there is on-going communication much earlier than TG6 between the materials development efforts and the engine development program. This interaction is important to insure that the materials effort continues to be targeted at the right application(s), that the required design practices for the new technology are being developed,

appropriate scalability and processability issues are being addressed, and inspectability methods and process limits are underway.

As the technology and product development programs progress in parallel, better definition of costs and benefits of the technology can be made, reinforcing the business case. This is important not only for the technologist, but also for the supplier base that requires lead-time to industrialize the new technology.

The material development process is complicated by the fact that within the materials field, various materials approaches vie for development resources. This is graphically illustrated in Fig. 8, which maps various material families on a plot of Strength versus Temperature. Nickel superalloys are being challenged on the low temperature end by titanium and intermetallic titanium aluminides, and on the high temperature end by ceramic matrix composite (CMC) materials and refractory metal intermetallics, such as niobium silicides.

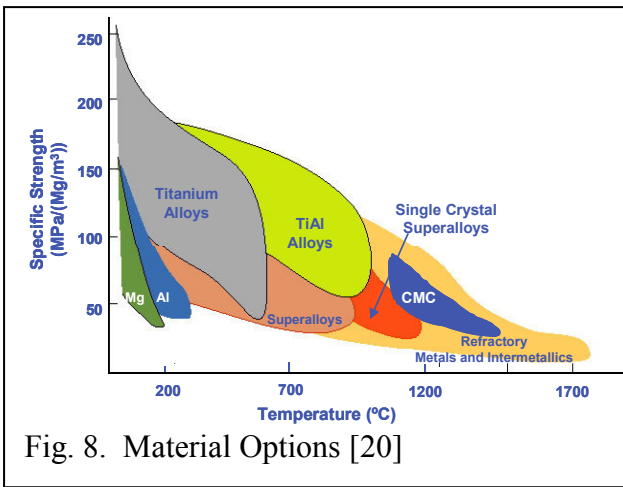


Fig. 8. Material Options [20]

From an engine design engineer perspective, having material options is desirable since it increases the opportunity to achieve the best match of material properties to design requirements. From a material developer viewpoint, the opportunity to present leading edge ideas as candidates to satisfy a defined need is also rewarding. This competitive approach opens the door to new ideas, and overcoming inertia and stagnation in materials technology. For example, superalloy airfoils are well established in the turbine section of the engine. But great strides are being made in the development of ceramic matrix composite

airfoils; the feasibility of using CMCs in this application is currently being established. Superalloy airfoil developers are responding to this challenge by an innovative multi-prong initiative that includes advancement in airfoil substrate materials, heat transfer technology, and airfoil coatings that allow longer operation at higher temperatures. Thus, the competition between these material systems has led to advancements across a broad front.

The “fundamental challenge” is to drastically reduce the development time for new materials and processes without adding development risk. The superalloy development sequence used during the past 50 years could be characterized, for the most part, as sequential, as shown in Fig 9.

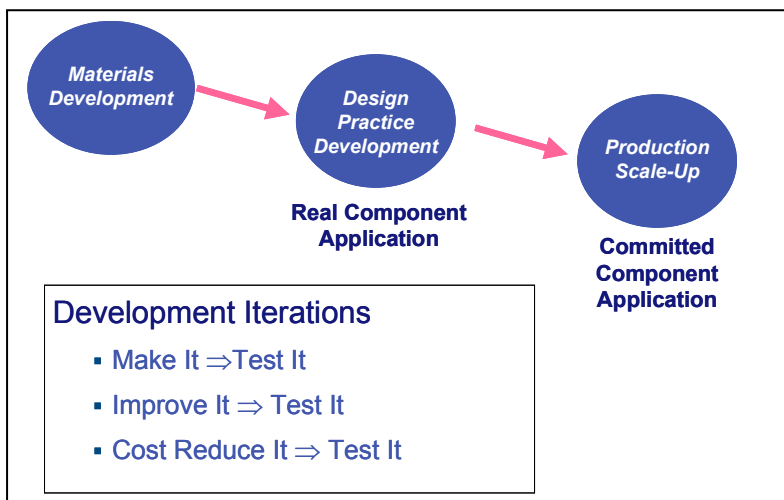


Fig. 9. Superalloy Development Sequence—Past

New materials were invented, and then a long process ensued to find a specific application, fill in all the other required details and establish a supply chain.

The current process avoids many of the pitfalls of the past, using integrated teams that employ analysis tools, that include materials and process modeling combined with design of critical experiments. Materials modeling tools that effectively combine heuristic and fundamental knowledge can rapidly

provide realistic estimates of material properties, providing an important element in the quest to

address the fundamental challenge. A representative example of how different models can be linked together to provide an estimate of material properties is depicted in Fig. 10.

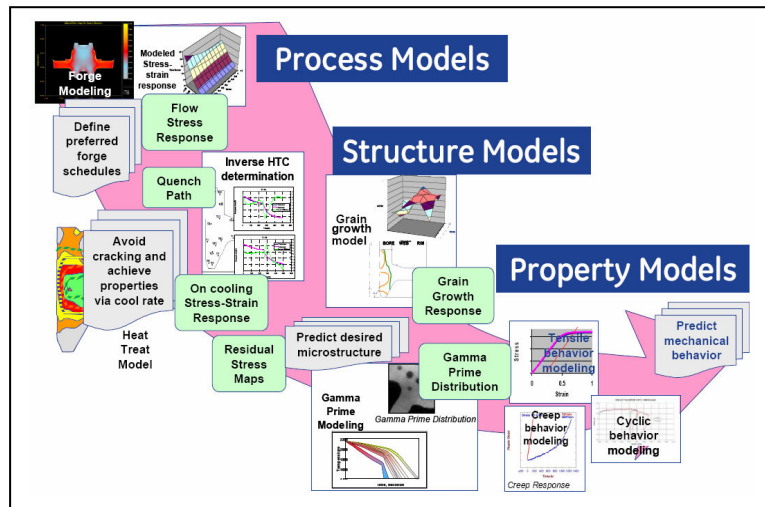


Fig. 10. Material Models

The current development approach is depicted in Fig 11. All together, it is resulting in considerable reduction in development time and resources. But progress is not as rapid as it could be since the teams are not fully integrated for several reasons that include:

- The tools that are being used across the teams are not standardized or not fully integrated.
- Legal issues regarding contractual terms and conditions, such as protection of proprietary data, retard progress. A complicating factor is the reality that team members can also be competitors on other projects, and thus there is a reluctance to share best ideas between potential and actual competitors. For instance, cooperating partners strive to add legal protection against possible future misuse of proprietary information on the part of the other team members.
- Different reward structures exist among industry, university, and government laboratory team members. This results in differing priorities that can affect timely completion of critical tasks.

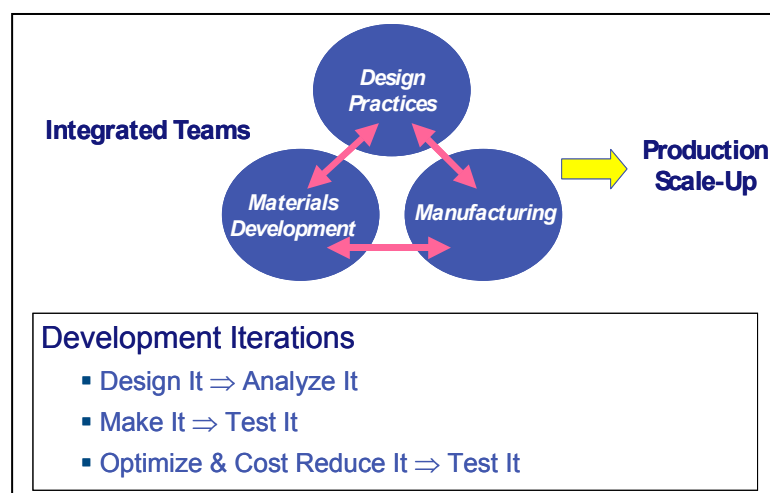


Fig. 11. Superalloy Development Sequence—Current Practice

The idealized goal for a fully integrated team is depicted in Fig 12; even though it may not be possible to achieve the ideal, it is a goal worth striving for.

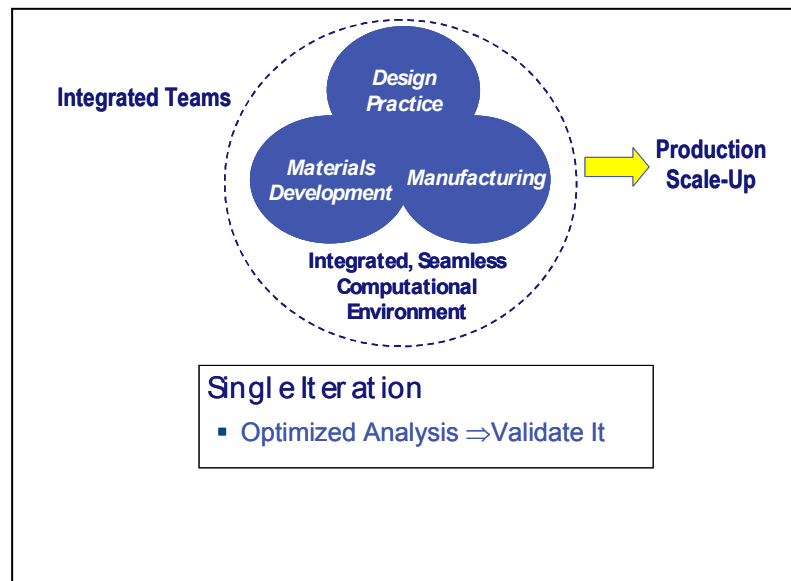


Fig. 12. Super Alloy Development Sequence—Ideal

### Summary

The first 60 years of jet-powered flight has been quite exciting, far exceeding expectations of most "experts." Materials and process advancements have played a key role in this adventure. The future is unknown, and predictions are inherently risky. However, the next 50 years of jet engines is sure to be as equally exciting, and there can be little doubt that progress in materials and processes will be pacing the advancements.

The history of materials and process development for jet engines contains several prominent themes that will continue to be major factors.

- Turning advanced design concepts into reality is often enabled by new materials and processes. Materials and design engineers have both benefited from, and enjoyed, the ongoing game of leapfrog.
- The high introductory cost of a new material or process can be offset by a compelling mission benefit, even in a cost-constrained business environment.
- The challenge of avoiding exceptionally deleterious defects that occur at very low frequencies significantly influences the development and application of high integrity structural materials.
- Each incremental gain in an alloy property is usually tempered by some corresponding debit. A key aspect of the development strategy involves determining the benefit, and understanding the debit, of each change. Therefore, providing balanced material properties throughout the different stress and temperatures regimes is critical to successful material development.
- A new class of structural materials, such as ceramic matrix composites and intermetallics, must vie for development resources with existing materials. This competitive process adds vibrancy and overcomes stagnation in materials technology.

- Usable material properties are governed by the type and frequency of defects arising from processing, not by the average property values that are determined by the chemistry and microstructure of the alloy.

The Grand Challenge for the materials development community is to mature new materials technology at a faster rate than the long drawn-out historical timeline. This accelerated schedule provides closer alignment to the product development cycle. Consequently, materials technology will be positioned to contribute significantly to the quest for improved aero-turbine engine performance.

The key elements of this new materials development paradigm include:

- The new paradigm is system engineering centric, requiring that proposed materials capability be aligned to design requirements, and critical-to-success metrics identified that can focus resources to assure implementation success. This requires tight linkage between materials technologists and the engineering design community, using the metric of “customer value” to guide the final selection of the technologies. This linkage insures that the appropriate engineering design practices are in place to allow usage of the material.
- Under this new paradigm, materials developers are encouraged to exercise creativity in establishing the feasibility of a new material. However feasibility is determined with respect to the needs of a particular component, rather than a generic set of requirements. These needs include prediction of component lifetime with respect to all possible material degradation modes in the anticipated service environment.
- Materials modeling and simulation are becoming essential tools. Material innovation requires exploring multiple paths to find the optimum solution. Laborious physical trial-and-error experiments aimed at finding the appropriate solution is too lengthily and costly to be the primary method of investigation. Computer-based analyses, followed by targeted physical experiments, can quickly determine feasibility and guide the scale-up effort for the desired materials solution.

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