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NASA Technical Memorandum 82626

Advanced Aircraft Engine Materials Trends

(NASA-TM-82626) ADVANCED AIRCRAFT ENGINE
MATERIALS TRENDS (NASA) 16 p HC A22/MF A01
CSCL 11F
N81-27259
Unclas
G3/26 26864

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JUL 1981
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Prepared for the
Twenty-sixth Annual International Gas Turbine Conference
sponsored by the American Society of Mechanical Engineers
Houston, Texas, March 8-12, 1981

NASA

E-979

ADVANCED AIRCRAFT ENGINE MATERIALS TRENDS

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ABSTRACT

Advances in gas turbine performance have been made possible by combinations of improved designs and improved materials. To support continuing U.S. engine performance improvements, the NASA Lewis Research Center has a materials research and technology program contributing to the national technology base for improved engine materials and assisting aircraft engine manufacturers and suppliers in developing new materials concepts through early engine demonstration tests. This paper will review recent activities of the Lewis Research Center which are directed toward developing materials for rotating hot section components for aircraft gas turbines. Turbine blade materials activities are directed at increasing metal temperatures approximately 100° C compared to current directionally solidified alloys by use of oxide-dispersion-strengthening or tungsten alloy wire reinforcement of nickel or iron base superalloys. The application of thermal barrier coatings offers a promise of increasing gas temperatures an additional 100° C with current cooling technology. For turbine disk alloys, activities are directed toward reducing the cost of turbine disks by 50 percent through near net shape fabrication of prealloyed powders as well as toward improved performance. In addition, advanced alloy concepts and fabrication methods for dual alloy disks are being studied as having potential for improving the life of future high performance disks and reducing the amount of strategic materials required in these components.

INTRODUCTION

During the three decades of jet powered commercial aviation, the performance of the engines has improved dramatically. For example, specific fuel consumption of current technology engines is about one third less than that of early commercial jet aircraft engines. This performance improvement has been achieved by a combination of improved design features and improved materials/manufacturing processes.

The economic pressures of rising fuel costs, environmental acceptability of engines and the strategic nature of engine construction materials continues to indicate a need for improved designs and more advanced material concepts. This paper reviews some of the activities of the NASA Lewis Research Center which are directed toward providing improved material systems for aircraft gas turbine engines. The specific materials to be discussed include those for rotating turbine components such as blades and disks.

TURBINE BLADE MATERIALS

Turbine blades are subject to the most severe combined stress/operating environment of the engine components. Consequently, there are several projects at the Lewis Research Center devoted to turbine blade materials. Figure 1 shows the increase in use temperature of superalloys over the past three decades. The increase in use temperature has averaged 8° to 9° C per year. To achieve that increase, however, a combination of improvements in both processing and alloy chemistry was required.

The vacuum induction melted polycrystalline alloys introduced into service in the early 60's had a use temperature of about 900° C. In the mid-70's, directionally solidified alloys which eliminated chordwise grain boundaries were being introduced and the use temperature increased to about 975° C. Other airfoil materials which are now being evaluated for near term incorporation in aircraft gas turbines include advanced directionally solidified alloys such as René 150 and directionally solidified single crystal alloys. The single crystal alloys eliminate all grain boundaries and thereby offer greater compositional freedom. To achieve still greater improvements, other directional alloys such as eutectic alloys, directionally recrystallized oxide-dispersion-strengthened superalloys, and fiber-reinforced alloys show varying potential for application toward the end of the 80's or in the 90's. While ceramics offer the greatest long term potential, it is unlikely that these materials will be available for man-rated aircraft during this century.

Directionally-Cast Superalloys

Two directionally solidified airfoils developed in our Materials for Advanced Turbine Engines (MATE) program at Garrett Turbine Engine Company, are shown in Fig. 2. The solid directionally solidified (DS) MAR-M 247 and single crystal (SC) NASAIR 100 (a modification of MAR-M 247) blades are intended to replace the conventionally cast, cooled blade. The DS blade allowed the turbine inlet temperature to remain at 1050° C, but because it did not require cooling, the engine's specific fuel consumption was reduced by 2.4 percent (Ref. 1) and the engine cost was reduced by 3.2 percent (Ref. 2) partly because of the lower manufacturing costs of solid blades compared to cooled blades. It is anticipated that the single crystal blade will permit the turbine inlet temperature to be further increased about 25° C permitting further improvements in the engine performance (Ref. 3).

Also under the MATE program, General Electric (Contract NAS3-20074) is developing technology to demonstrate the use of an advanced DS alloy, René 150 blade alloy in a CF6 turbofan. The objective of that project is to reduce turbine cooling air and engine SFC by using a DS alloy having improved high temperature capabilities. Such a cooled DS René 150 turbine blade is shown in Fig. 3.

Oxide Dispersion Strengthened Superalloys

To obtain greater increases in allowable metal temperature, oxide-dispersion strengthened superalloys offer potential. The first generation alloy of this type is alloy MA 6000E. It is a gamma prime strengthened superalloy to which fine, stable oxide particles have been added. It was developed in a joint Lewis Research Center/International Nickel Co. research effort (Ref. 4). The gamma prime phase provides effective creep-rupture strengthening to about 1000° C, and the oxide particles continue to provide creep rupture resistance to about 1200° C, as shown in Fig. 4.

The process steps by which an oxide-dispersion-strengthened superalloy is made are also shown in Fig. 4. Metal powders, elemental and prealloyed, are mixed together with oxides in a high-energy-stirred mill that kneads the fine oxides thoroughly into the metal. The very homogeneous powder that results is sealed in cans and consolidated by extrusion. Optionally, hot rolling may follow. Finally, the hot-worked product is given its elongated microstructure by directional recrystallization in a thermal gradient. The macro and microstructures of the oxide-dispersion-strengthened alloy MA 6000E are also shown in Fig. 4. The highly elongated grain structure shown in the macrograph is oriented in the direction of highest applied stress (i.e., along the axis of a blade. There are essentially no transverse grain boundaries available at which thermal fatigue cracks can begin. The microstructure shows both cubic gamma-prime precipitates (the traditional strengthening phase in superalloys) and the very fine oxide particles that are within both the gamma prime and gamma phases. This oxide-dispersion-strengthened alloy, MA 6000E, has generated a great deal of interest among engine manufacturers, particularly for the smaller engines that are relatively difficult to cool. The Lewis Research Center is currently accelerating this technology by working with the Garrett Turbine Engine Company and International Nickel Company (Contract NAS3-20073) to demonstrate the use of MA 6000E turbine blades in a small turbofan engine under the MATE Program.

Fiber-Reinforced Superalloys

A third family of materials with a directional structure that offers the potential for higher operating temperatures, as shown in Fig. 1, is the fiber-reinforced superalloys (FRS). These are composite materials that take advantage of the high strength at high temperatures of reinforcing fibers such as refractory metal alloy wires as well as oxide or carbide filaments. The problems of brittle failure of ceramic fibers or of the low oxidation resistance of the refractory metal fibers can be reduced markedly by embedding the fibers in a ductile superalloy matrix, which provides toughness and resistance to environmental attack in the severe turbine environment. The early experimental problems encountered in studies with brittle ceramic fibers caused the current efforts to be focused on the more ductile refractory-metal-reinforced superalloys. A tungsten-fiber-reinforced superalloy (TFRS) is the primary system. This discussion will be concerned with TFRS, which is the most mature example of a fiber-reinforced superalloy material. Advanced efforts are aimed at solving the problems with ceramic fibers.

Laboratory tests of tungsten wire in a highly oxidation-resistant, iron base alloy matrix, Fe-Cr-Al-Y, have shown excellent high-temperature strength, oxidation and fatigue resistance, and wire-matrix compatibility. These results suggest excellent potential for several turbine component applications. As much as a seven-fold strength advantage in 1000-hour rupture strength at 1000° C could be obtained for TFRS over conventional superalloys (Refs. 3 and 6). The high thermal conductivity of tungsten wire also increases the thermal conductivity of TFRS, typically to about twice the thermal conductivity of conventional superalloys. This advantage can be used to increase the effectiveness of cooled turbine components, either to increase life at a given cooling airflow or to increase engine efficiency at a reduced cooling airflow.

Fabrication processing of TFRS for turbine components is shown schematically in Fig. 5. The process is based on the technology previously developed for lower temperature components such as boron-aluminum and graphite-epoxy. A filament mat and matrix alloy foil are combined to form a composite monotape, which is then cut into plies. The plies are stacked in the proper sequence and diffusion bonded to form a component or component subassembly. This basic fabrication process has been used to fabricate a hollow, air-cooled turbine blade with trailing-edge cooling slots from TFRS. This blade matched the external contours of a first-stage JT9D blade. Even though the design of the blade was not optimized it was only 10 percent heavier than the standard superalloy blade (Ref. 7).

Thermal Barrier Coatings

As an alternative to developing materials which are capable of operation at higher temperatures and stresses, the material temperature can be reduced by applying thermally insulating coatings on cooled turbine airfoils. These coatings, often referred to as thermal barrier coatings (TBC), have been under development at the Lewis Research Center for over a decade. This technology offers a promise of increasing turbine gas temperature 100° C with current air cooling technology or alternatively to significantly reduce the amount of cooling air required at the same gas temperature. This is shown schematically in Fig. 6 (top). The key technology required to advance this concept appears to be the compatibility of the ceramic coating and an intermediate metallic bond coat which might be compared to a high temperature glue used to hold the ceramic to the substrate. In addition, the brittle ceramics must be deposited such that they can tolerate the thermal strains caused by the difference in thermal expansion between the ceramics and the metal. Figure 6 also shows an example of a bond coat and thermal barrier coating which were deposited by a plasma spray process.

Early work at the Lewis Research Center identified a turbine blade coating system which survived 500 engine cycles in a J75 research engine (Ref. 8). More recent tests performed at Pratt & Whitney Aircraft (Ref. 9), revealed that further development was required for adaptation of the coating system for use in current commercial engines. Subsequent studies showed that this durability of the coating system could be improved by modifying the composition of the bond coat and the ceramic coat. An example of this is shown in Fig. 6 (right hand side). It can be seen that the coating life is substantially better when the zirconia coating has about 6 percent yttrium oxide added and the bond coat has about 0.15 percent yttrium.

One of the most recent demonstrations of the state-of-the-art of thermal barrier coatings was performed by Pratt & Whitney Aircraft as part of a NASA program (Ref. 10) to reduce fuel consumption in current commercial aircraft. Figure 7 shows JT9D first stage turbine vanes after being exposed to 1000 engine cycles. These vanes had thermal barrier coatings applied to their platforms and a reduction in the number of film cooling holes. Of 36 coated vanes only 9 showed slight to moderate coating spalling and no adverse effect on the platforms with reduced cooling. The remaining 27 showed no apparent distress to the coating or platforms.

TURBINE DISK MATERIALS

Disks operate at significantly lower temperatures than do turbine blades. However, as high-mass rotating components, their potential failure could pose a serious threat to safe engine operation. The requirements for nickel-base superalloys to be used as disks are somewhat different from the requirements for hot section airfoil components. For instance, environmental attack is minimized because of the lower operating temperatures (400° to 700° C) and reduced exposure to combustion products. Since disks are highly stressed parts, the first concern must be with strength - especially uniformity of strength - so that designs can be optimized without some small, weaker area developing a crack prematurely. Disks are large and heavy and the commonly used nickel-base superalloys contain significant amounts of strategic alloying elements (cobalt and chromium). Therefore, raw material utilization, cost, and processing efficiency are becoming increasingly important considerations in disk production. And finally, resistance to fatigue crack initiation and propagation are extremely important at the hub and bolt circles because long-life service requirements impose numerous cyclic loads on disks.

The traditional practice of manufacturing disks has been to cast ingots and then to forge and machine them to a shape compatible with ultrasonic inspection. Following ultrasonic inspection, final machining would yield the finished disk. As higher strength disk alloys were developed, as shown in Fig. 8, it was also found that the newer, stronger alloys were much more difficult to forge into a uniform product. Some of the forging problems were found to be associated with the natural segregation of elements which occur when ingots are cast.

Powder Metallurgy Superalloys

To reduce the scale in which the segregation occurs, microcastings or powder superalloys were made and were found to be more easily processed. In a recently completed NASA funded MATE project at General Electric a hot isostatically pressed powder (HIP) René 95 billet was hot die forged to near the ultrasonic inspection shape of a CFM 56 high pressure compressor disk shown in Fig. 9. The process demonstrated a 54 percent reduction in input weight and a 35 percent cost reduction compared to conventional cast ingot forging and machining (Ref. 11).

An obvious extension of HIP and forge processing is to eliminate the forging step and directly HIP to near the ultrasonic inspection shape. This technology was first demonstrated for commercial aviation in a MATE project for NASA performed by Pratt & Whitney Aircraft (Refs. 12 and 13). A JT8D-17 high pressure turbine disk was HIPed to near the ultrasonic inspection shape from low carbon Astroloy as shown in Fig. 10. The project demonstrated a 30 percent reduction in input material and a reduction of 20 percent in cost compared to the forging it would replace.

For both of the examples cited, it is worth noting that the input weight savings offer a significant reduction in the requirements for strategic materials. Finished turbine disks often weigh more than 50 Kg and the advanced alloys used to make disks typically contain from about 8 to nearly 20 percent cobalt. Because the United States imports about 90 percent of its cobalt a 20-54 percent input weight reduction offers significant reductions in imported cobalt requirements.

Dual Alloy Disks

An exciting new concept for tailoring the properties for advanced disks is illustrated in Fig. 11. The dual alloy disk concept uses powder metallurgy to tailor the properties of disks to meet the widely different requirements at the bore and rim of the disk. The alloy used for the bore can be optimized for high strength and low cycle fatigue resistance at the moderate bore temperatures. The alloy used for the rim can be optimized for the higher temperature-lower strength requirements at the rim. A dual alloy disk can be produced by centrifugally filling the rim portion of a rotating can with an alloy powder selected for high-temperature creep resistance. The central portion of the can is then filled with another alloy powder selected for superior fatigue resistance in the lower temperature bore. The filled can is then hot isostatically pressed, as described previously. An alternative approach being evaluated consists of first consolidating the rim and then filling the bore with the same or different alloy powder, followed by consolidation and diffusion bonding in a second HIP cycle. The dual alloy disk concept is still early in its development process in a NASA contract with TRW (Contract NAS3-21351), and significant testing and evaluation remain to be conducted before the full benefits are achieved.

Fatigue Behavior of Disk Alloys

As part of the continuing efforts at NASA Lewis to contribute to the materials technology base for hotter and more efficient turbine engines, we are seeking to an improved understanding of the fundamental role of superalloy composition, microstructure, environment, and deformation mechanisms on the processes of fatigue crack initiation and propagation in turbine disks. Lewis has recently completed an evaluation of the fatigue and creep fatigue behavior of several commercially available and developmental powder metallurgy superalloys (Refs. 14 to 16). The results are illustrated in Fig. 12. Crack initiation life at 650° C is significantly influenced by alloy strength level and ductility, and the type of fatigue cycle. Specifically, at strain ranges typical of commercial engine turbine disks, the disk life (as measured by time to crack initiation) is increased as alloy strength increases. For applications permitting higher strain ranges, the life is increased as the alloy ductility is increased. For all strain ranges, the introduction of tensile creep dwell time to the fatigue cycle decreases the life by promoting earlier crack initiation. In the fatigue tests, the high strength alloys generally failed in an intergranular mode, while the low strength alloys generally failed in a transgranular mode. When the tensile creep dwell time was added to the test cycle, all the alloys studied failed in an intergranular mode.

The crack growth rate measurements suggest that the higher strength alloys have higher crack growth rates in both the fatigue and creep-fatigue test cycles. Thus, while extremely high strength alloys may appear attractive on the basis of time to crack initiation, their extremely high crack growth rates may be a severe impediment to turbine disk application. Thus, greater understanding of the relationships between strength, fatigue resistance and crack growth rates are necessary to achieve improved materials for both disk bores and rims as discussed above for dual alloy disks.

CONCLUDING REMARKS

This paper has reviewed some recent developments from Lewis Research Center's in-house and contractural efforts. These developments suggest that for the near future, turbine blade improvements will result from using single crystal and oxide dispersion strengthened superalloys. The application of thermal barrier coatings offers the promise of extending the use of those alloys in engine with an additional 100° C in gas temperature. Tungsten-wire-reinforced superalloys offer a potential of further extending metal temperature about 100° C, but this technology is still in its infancy and will require several more years of effort to achieve its potential.

Recent developments in disk materials have been directed toward fabrication economies. The use of powder metallurgy superalloys has resulted in cost reductions of 20-35 percent compared to conventional forgings and has allowed reductions in input weights of up to 54 percent. The future for disk materials may involve dual alloy processing which will allow a better balance of properties at both the cool highly loaded bore and the hot rim sections of disks. The properties and fabrication of such disks are currently being studied.

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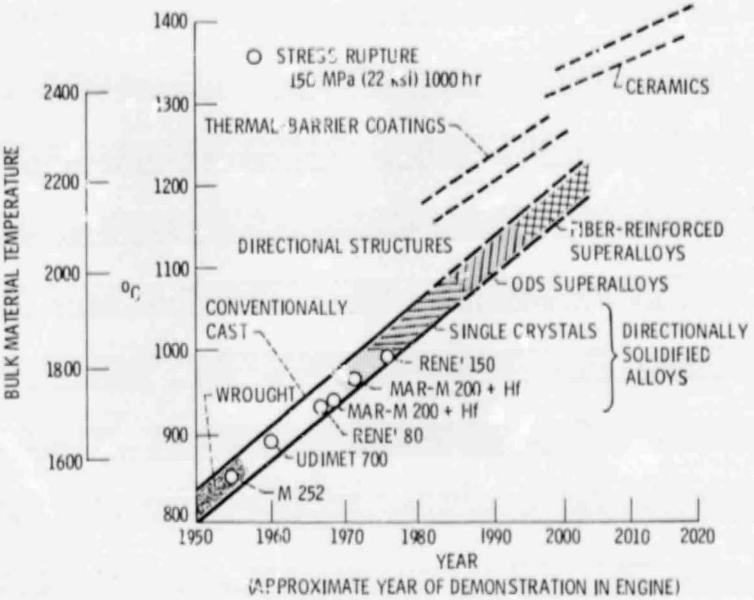


Figure 1. - Progress in turbine blade materials.

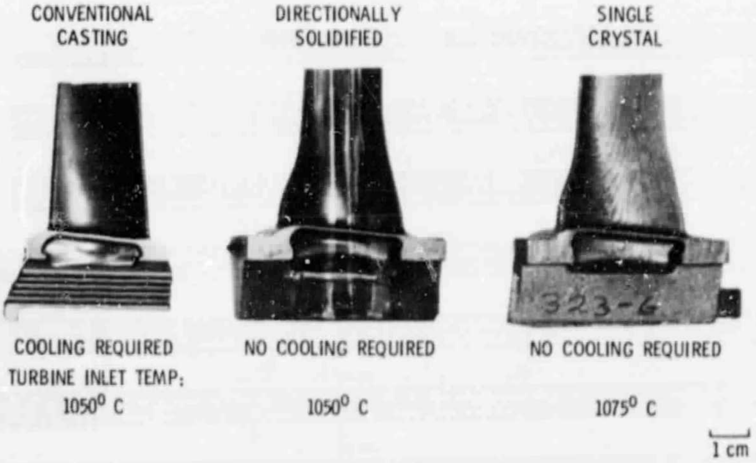


Figure 2. - Garrett TFE 731 turbine blades.

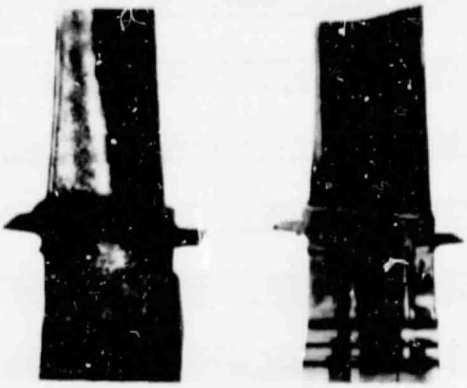


Figure 3. - General electric CF6-50 blades.

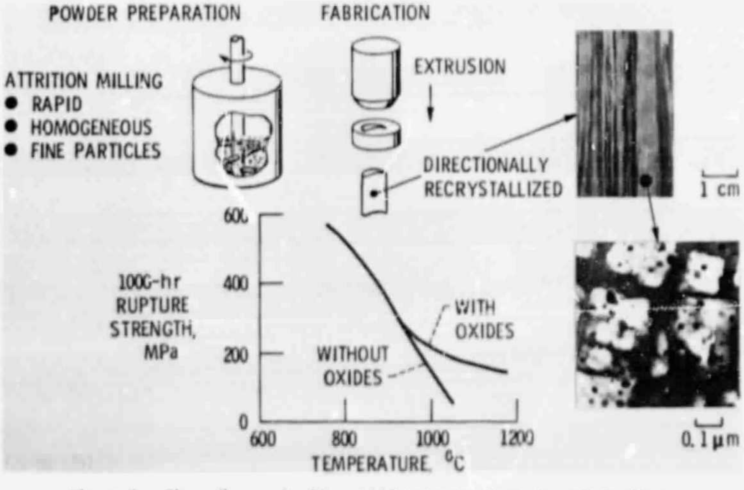


Figure 4. - Fine, dispersed oxides add high-temperature strength to alloys.

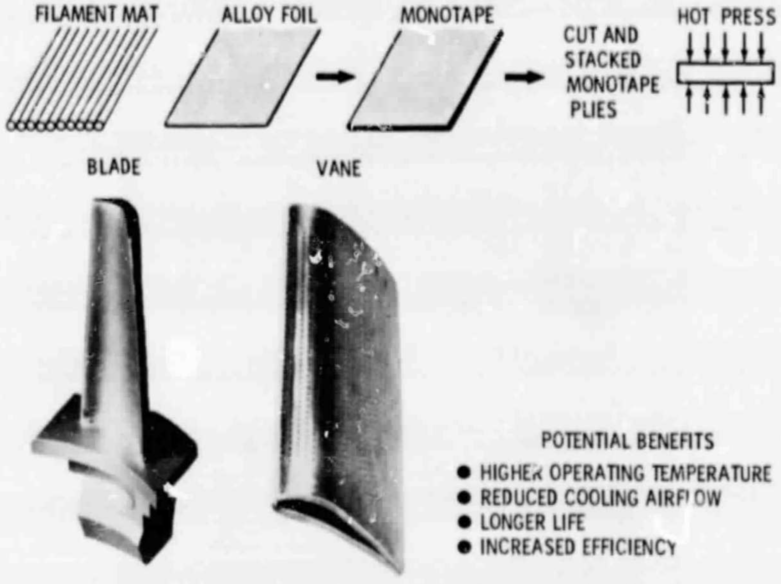


Figure 5. - Fiber - reinforced superalloy turbine components.

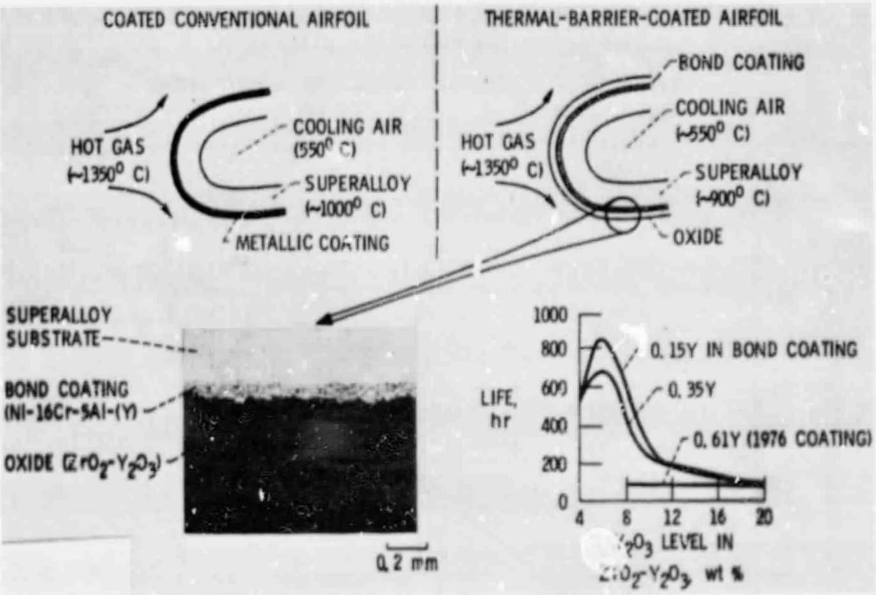
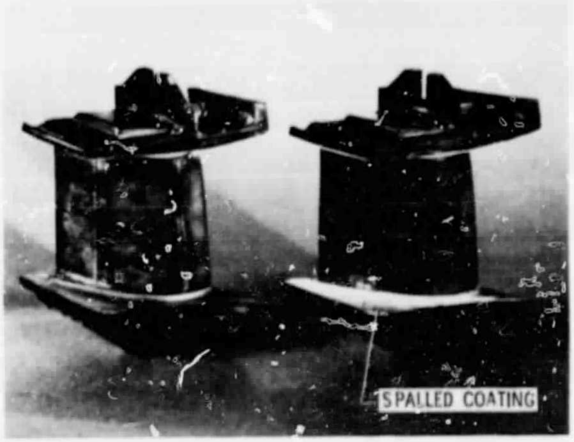


Figure 6. - Thermal-barrier coating of turbine airfoils.

(a) PRE-TEST CONDITION.



(b) POST-TEST CONDITION SHOWING COATING THAT SURVIVED INTACT (ON LEFT) AND COATING THAT SPALLED (ON RIGHT).

Figure 7. - First stage vanes with thermal barrier ceramic coatings used in engine test.

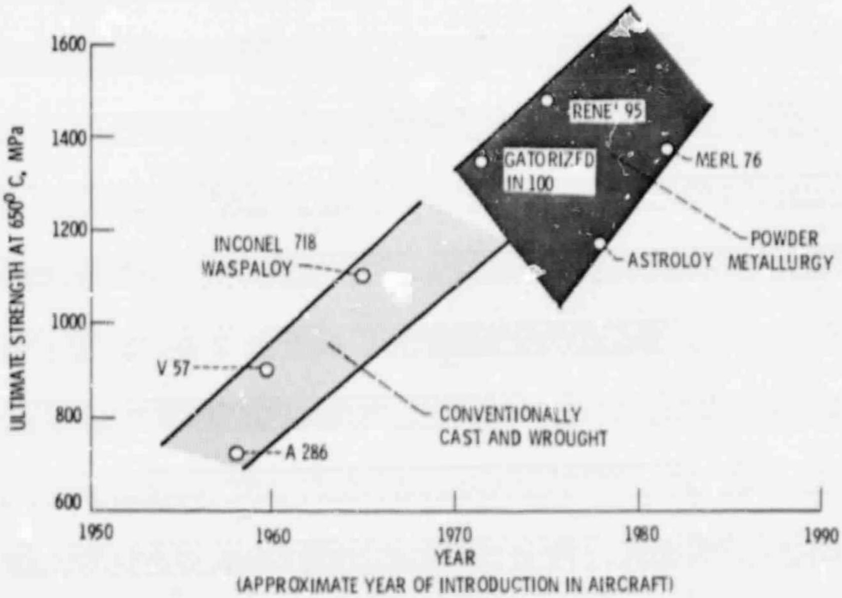


Figure 8. - Strength trends in turbine disk materials.

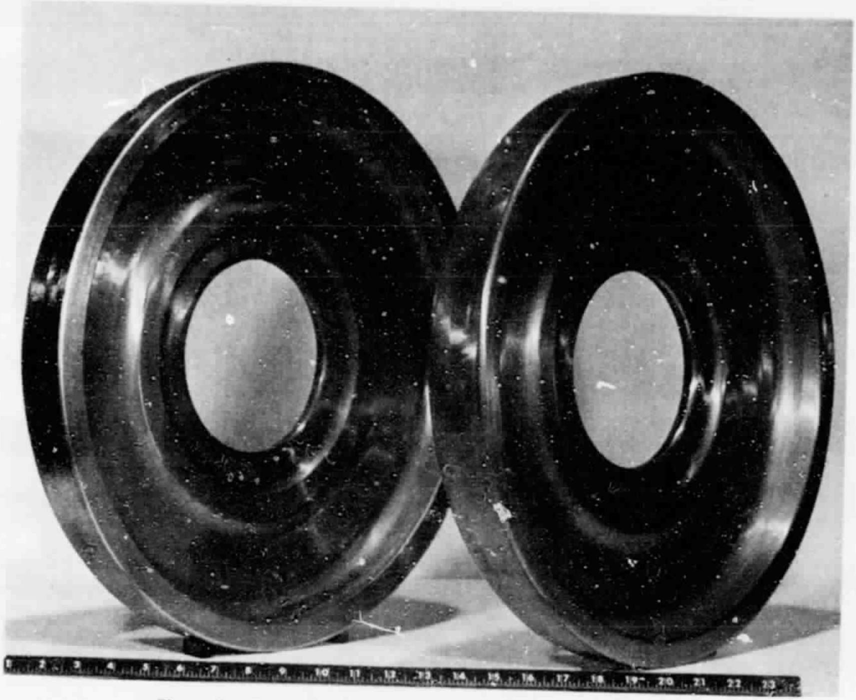


Figure 9. - Rene' 95 hot die forgings for CFM 56 compressor disks.

Figure 10. - As-HIP shape of LC Astroloy for JT8D turbine disk.

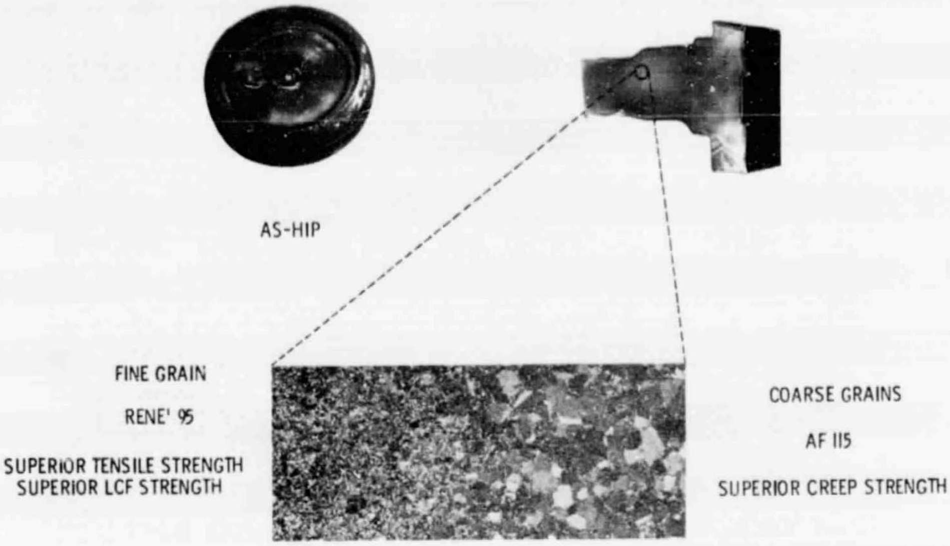


Figure 11. - Dual alloy turbine disk.

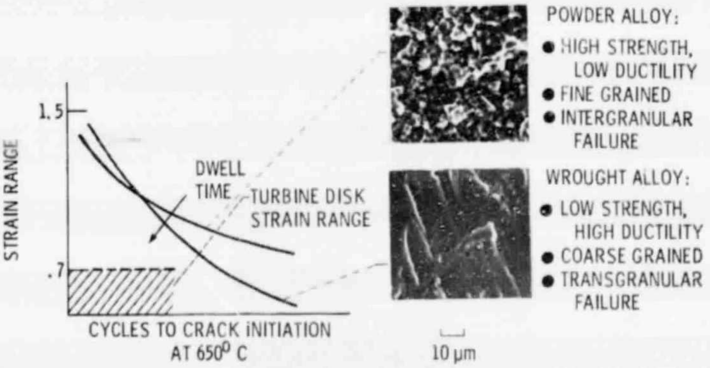


Figure 12. - Fatigue behavior of powder metallurgy disk alloys.