

ADVANCED MATERIALS RESEARCH FOR LONG-HAUL AIRCRAFT TURBINES ENGINES

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SUMMARY

The use of improved materials for aircraft turbine-engine components has significantly increased performance. The components are stronger and lighter, and have higher use-temperatures and longer service lives. The improved materials may be used for components in both high- and low-temperature areas of the engines. Fiber composites and high-temperature alloys are the major advanced materials being studied for use in turbine-engine components. The engine components for which these materials are under study include fan blades, fan-exit guide vanes, fan frame and case, containment ring, nacelle, combustor, and turbine vanes, blades, and disks.

Cost-benefit analyses have shown that a significant fuel saving can be achieved by use of these materials. For example, fan blades, turbine disks, combustor, seals, and high-pressure turbine blades and vanes of these advanced materials could save a commercial fleet 600 million gallons of fuel a year.

This paper reviews the status of research efforts to apply low-to-intermediate temperature composite materials and advanced high-temperature materials and their application to the engine components. It emphasizes emerging materials technologies and their potential benefits to aircraft gas turbines. The problems are identified, and the general state of readiness of the technology for near-term use is assessed.

INTRODUCTION

Materials and processing technology continue to have a key role in the development of advanced aircraft gas-turbine engines. This paper highlights the materials technology areas that are expected to significantly affect future aircraft turbine-engine development. Approaches to the development of improved materials technology as well as its advances are included. Emphasis is placed on emerging material technologies that may be included in NASA-sponsored materials programs or aircraft-engine technology programs. These programs include the study of the components shown in figure 1: fan blades, turbine blades and vanes, turbine disks, combustors and seals.

The potential benefits of using these components are listed in table I. In recent NASA sponsored studies (refs. 1 to 6), most component-material combinations were analyzed for their potential economic benefit to commercial transport engines. These studies reflect the changing climate in materials develop-

ment from the dominance of engine performance in the past decade to that of economic benefits (ref. 7). Several factors account for this change, including the more restricted availability of development funds, a lower frequency of new engine applications, greater pressures to reduce engine maintenance costs, and greater emphasis on fuel economy.

Benefits of the advanced material technologies described herein are presented in terms of higher temperature capability, lower weight, or lower cost. It should be noted that the emphasis placed on materials with higher temperature capability does not mean that turbine-inlet temperatures in advanced engines will be higher. Most likely, this higher temperature capability would be used by the designer to reduce turbine cooling requirements or to extend component life. These types of performance improvements usually show the greatest overall economic benefit to the commercial aircraft system.

COMPOSITE FAN BLADES

Payoff studies have indicated that composite fan blades will be lighter weight, stronger, and stiffer than the current standard forged titanium. These advantages can permit improved engine performance, greater fuel economy, and reduced direct operating costs. A major obstacle to the use of composite fan blades has been their susceptibility to foreign-object damage (FOD). Foreign-object damage can be caused by rivets, ice balls, rocks, and birds. Bird ingestion is a major flight safety hazard (ref. 8). Although most bird ingestion incidents are harmless, some collisions with larger birds can cause significant damage. For example, the titanium fan blade shown in figure 2 was damaged by a 1-kg (2- to 2.5-lb) gull. Damage to composite blades in simulated service rig tests are shown in the lower figure.

Research has been directed toward improving the resistance of composite fan compressor blades (refs. 8 to 10). Progress in this research is illustrated in figure 3. A joint Air Force and NASA program is aimed at demonstrating the application of boron/aluminum (B/Al) composites to first-stage J-79 blades (ref. 11). The production J-79 blade is made of 403 stainless steel and weighs 450 g (1 lb). In impact testing of stainless-steel blades (single-blade whirling-arm tests), an 85-g (3-oz) starling caused local bending. Early B/Al blades were broken into several pieces by a similar impact. Application of NASA developed, more-impact-resistant B/Al produced improved, but inconsistent FOD results (1975-76): Some suffered only minimal damage, while others suffered extensive delamination and deformation. Later results (1977) showed no material loss and only minimal delamination. Blades in an actual engine could continue to operate normally.

The improved B/Al technology that led to these encouraging results is being included in composite FOD improvement programs aimed at large, high-bypass-engine fan blades. Several designs and materials combinations are included in the program (fig. 4). All the designs shown include the removal of the mid-span damper. The solid design is being studied with all three composite materials - the polymer matrix, metal matrix, and superhybrid combination of metal matrix and polymer matrix composites. The spar-shell design has the advantage of

a proven titanium root attachment and a titanium spar. This design is being pursued using B/Al and superhybrid composite airfoil shells. Although the hollow design can be lighter than the solid, or spar shell, it is more difficult to fabricate and, possibly, less FOD resistant. The design using hollow titanium blades is also under consideration. Further studies of this design approach using composites are expected. The patch design employs a composite inlay to stiffen a titanium blade. The composite patch increases aeromechanical stability and can permit the removal of the midspan damper, which increases aerodynamic efficiency and reduces fabrication cost. None of the design approaches have demonstrated the degree of confidence for service readiness for application to commercial engines.

A number of tests are being used to demonstrate fan blade FOD resistance (fig. 5). Single-blade rig tests are performed to demonstrate, under carefully controlled conditions, the range of severity of bird impacts that can be expected in engine service. These tests will be used to screen designs and materials combinations for the more costly full-stage rig and ground engine tests needed to qualify composite fan blades for application. All the candidate composite materials and design for large, high-bypass-engine fan blades are currently in the single-blade-rig, FOD phase of the tests. Although the outlook for composite fan blades is encouraging, a considerable amount of work has to be completed before they are ready for engine service.

TURBINE BLADES

Progress in the development of turbine-blade materials is illustrated in figure 6. As shown, conventionally cast alloys such as René 80 provide blade-metal use temperatures in the range of 900° to 950° C (1650° to 1740° F). The application of directional solidification to conventional alloys provides a modest gain in use temperature and significantly improves resistance to thermal fatigue (ref. 12). Because future engine requirements exceed the capabilities of conventional alloys, a new class of materials is being developed to meet the need for turbine blades that must operate at least 100° C (180° F) higher than present blades. These new materials are directional structures (fig. 7), which comprise single-crystal superalloys, eutectic alloys, wire-reinforced superalloys, and oxide dispersion-strengthened (ODS) alloys (refs. 13 to 19).

Single-Crystal Superalloys

Single-crystal superalloys have improved creep strength, ductility, and resistance to thermal fatigue. They are produced by a directional-solidification process similar to that used for directionally solidified, columnar-grained superalloys. In the near future development of single-crystal blade alloys is expected to emphasize modification of present high-strength superalloys. These modifications are likely to include the elimination of grain-boundary strengtheners such as boron, carbon, and zirconium; and the substitution of other elements for added γ' strengthening. Later, emphasis is likely to be placed on tailoring new alloy compositions specifically to achieve higher strength single-crystal blade alloys. Cast blade costs for single-crystal blades are likely to

be less than DS-columnar-grained alloys, since the single-crystal alloys normally contain fewer reactive elements that tend to cause blade defects during the casting process. A potential near-term application of single-crystal blades includes the use of the low-cost, exothermic DS casting process using a modified Mar-M247 blade alloy (ref. 20). This program emphasizes uncoated, single-crystal blade applications to general aviation turbine engines. Similar programs are anticipated in the near term for advanced commercial aircraft engines.

Directionally Solidified Eutectics

Directionally solidified eutectics are a relatively new class of blade materials. They have been studied extensively in the past few years under the sponsorship of NASA and DOD. Examples of eutectic alloys under evaluation include $\gamma/\gamma' - \delta$ and NiTaC-13, which have a nickel-alloy matrix reinforced with platelets and fibers, respectively. A typical microstructure of these alloys is shown in the photograph on the left of figure 8. The $\gamma/\gamma' - \delta$ and NiTaC-13 eutectics have an estimated 50° C (90° F) advantage over conventional superalloys. However, either their transverse properties or castability will probably limit their engine use. More important, the high casting cost (twice the conventional DS superalloy cast, as indicated in ref. 21), due to their slow growth requirements and mold reactivity, precludes their consideration for near-term commercial applications. Advanced eutectic-alloy development programs are focused on the required advances in technology needed to bring the DS eutectics to a state of readiness for engine application. Approaches have been identified to improve critical mechanical properties and reduce casting costs. The potential in improved engine performance offered by the eutectics certainly warrants the significant research and technology effort underway.

Wire-Reinforced Superalloy Composites

Wire-reinforced superalloy composites of interest for turbine blades combine the excellent high-temperature strength of a refractory metal, such as tungsten wire, with the oxidation resistance and toughness of a superalloy matrix. Such a composite is illustrated in the right-panel photograph of figure 8 in which tungsten wires, about 0.04 cm in diameter, are embedded in a superalloy matrix. Similar composites, using a highly oxidation-resistant iron-alloy matrix, Fe-Cr-Al-Y, have shown excellent potential for turbine-blade application. These wire-reinforced composites have the highest temperature capability of the directional structures under consideration. Although the technology for these composites is not as advanced as that of DS eutectics, sufficient studies have been conducted to demonstrate their feasibility as a turbine-blade material in terms of strength, oxidation, and fatigue resistance, and wire-matrix compatibility. Also, a potential low-cost fabrication method (fig. 9) has been demonstrated using a monolayer-tape process similar to that developed for metallic-composite fan and compressor blades (ref. 22). Concepts for selective reinforcement to achieve blade densities comparable with superalloys and concepts for blade cooling show promise for advanced turbine-blade applications. Orderly laboratory development of the excellent high-temperature potential of these composite blade materials is expected to continue.

Oxide Dispersion-Strengthened Alloys

Recent advances in the production of oxide dispersion-strengthened alloys have introduced ODS- γ' superalloys as a candidate turbine-blade material. These alloys combine both γ' and oxide-dispersion strengthening to achieve high strength at intermediate and elevated temperatures. Directional structures are achieved in these alloys by a solid-state transformation (directional recrystallization and grain growth) that aligns the grains in the principal stress direction. Their potential for turbine-blade applications, other than high strength, is not yet defined because of their relatively new status. A potential problem may be low transverse ductility, which is usually characteristic of the ODS materials. Current programs are underway to better define the long-range potential of the ODS- γ' alloys for turbine blade applications.

TURBINE DISKS

Progress in the development of turbine disk alloys is illustrated in figure 10 using the 650° C (1200° F) yield strength as a reference. As indicated, improvements in conventional alloys have doubled the strength of turbine disks over the past two decades. For future disk applications, prealloyed-powder-metallurgy (PM) processing will be emphasized rather than the conventional approach of using cast ingots for later forging and machining to size. The PM approach offers two distinct advantages: First, substantial improvements in strength can be achieved (fig. 10) by specifically designing the alloys to accommodate larger quantities of strengtheners without encountering the segregation problems that occur during casting. In addition, the PM process affords improved structural homogeneity, which is expected to improve fatigue resistance even at the higher strength levels. Second, substantial reductions in disk manufacturing costs can be achieved by the PM approach (fig. 11). In the state-of-the-art practice, disks are made by vacuum melting, forging, and machining operations that result in a material utilization of about 40 percent. In the current PM approach, disks are made by forging a preform produced by hot isostatic pressing of a prealloyed powder. The material utilization for the latter approach is about 70 percent. In addition to the saving in material, about a 40-percent saving in machining costs is achieved because fewer steps are required (ref. 23).

For the longer-term, direct consolidation of disks from the prealloyed powder by hot, isostatic-compaction techniques is envisioned. The cost-reduction potential of this method is about 50 percent. Both PM disk alloy and process developments are underway to meet the anticipated requirements of advanced turbine engines (refs. 17, 24, and 25).

VANES, COMBUSTORS, AND SHROUDS

These turbine components must withstand very high temperatures, but the mechanical stresses are relatively low. For the stator vanes, ODS alloys offer a significant advantage over currently used conventionally cast alloys. (See fig. 12.) The ODS alloys have greater microstructural stability and overtemper-

ature capability (ref. 26). Their overtemperature capability is illustrated in figure 13, which compares a conventionally cast Mar-M-509 vane and an ODS alloy (TD-NiCr) vane. These vanes, contained in the same nozzle assembly, were subjected to an inadvertent overtemperature in an experimental engine test. Although cooled, the cast vanes melted, whereas the uncooled ODS alloy vanes were unaffected. In continuing studies, good engine performance has been achieved with the advanced ODS Ni-Cr alloy, Inconel MA-754 (ref. 27). Efforts are underway to develop and scale up low-cost vane fabrication technology for advanced engine applications (refs. 28 and 29).

Both the DS eutectic alloys and the wire-reinforced superalloys discussed previously for blade applications are potential vane materials for advanced turbine engines. Currently, they appear to be competitive with the advanced ODS alloys such as Inconel MA-754.

Ceramics such as SiC and Si₃N₄ also are candidates for engine vane application. (See fig. 12.) Their high-temperature capability far exceeds that of the other materials noted. However, the brittle nature of ceramics is a major deterrent to their use in aircraft engines. Progress in the use of these ceramics in related applications such as ground transportation (ref. 30) is likely to provide the technology and confidence needed to consider ceramics for aircraft engines in the future.

Combustors, including the liners and transition ducting, require sheet alloys with good forming and welding characteristics. Current combustor materials include alloys such as Hastelloy X and HS-188. ODS alloys in sheet form have both higher use temperature capability (about 100° C (180° F)) and significantly better oxidation resistance than current materials. Applying advanced ODS alloys such as Inconel MA-956 and HDS-8077 will require changes in combustor design to accommodate the relatively low ductility of the ODS alloys at elevated temperatures. Also, combustor fabrication techniques will require modification to compensate for the low high-temperature strength of fusion welds in ODS alloys. However, the temperature advantage and improved durability expected from ODS alloys appear to be sufficiently attractive to warrant their use in advanced turbine engines.

Decreasing the clearance between the blade tip and the inner wall of the turbine seal can significantly increase gas-turbine-engine performance. As shown schematically in figure 14, clearance increases during engine operation cause losses in thrust and fuel economy. A 1-percent turbine efficiency penalty has been estimated for a 0.025-cm (0.010-in.) increase in first-stage turbine blade tip clearance.

Improvements in turbine shroud materials have focused on the use of the more oxidation resistant NiCrAl alloys (ref. 31). Significant improvements in clearance control and shroud life have been achieved. Future efforts will likely emphasize both turbine-blade-tip treatments and improved shroud materials to maintain close clearance control and thereby improve engine fuel economy. Ceramics, similar to those used for vanes, are good candidates for advanced shroud applications (refs. 32 and 33). Turbine shrouds, being lower risk components, will probably be the first ceramic components used in advanced aircraft

engines. Turbine-blade-tip treatments are likely to include the use of more oxidation-resistant tip alloys, such as NiCrAl, with an abrasive tip to allow incursion into the shroud under abnormal engine operating conditions. In addition to the use of low-expansion alloys for turbine seals, support studies will yield further improvements in clearance control. Approaches such as those described are becoming increasingly important to extend blade-tip life, to control seal leakage, and, thereby, to increase fuel economy.

SUMMARY OF RESULTS

The use of advanced materials in aircraft gas-turbine engines will permit substantial economic benefits. The achievement of these benefits, with some component-material combinations, will require considerably more research, while others have a much shorter term application potential.

Composite fan blades offer the potential for a significant advantage over titanium blades, however, their resistance to foreign object damage must be increased. A series of tests must be successfully completed to assure readiness before a commitment to application can be undertaken.

High-temperature directionally structured materials for turbine airfoils include shorter term applications using directionally solidified polycrystalline and monocrystalline alloys. To achieve the higher temperature potential of DS eutectics, ODS superalloys and tungsten fiber-reinforced superalloys will require substantially more research. These directional structures have properties that will permit 50° to 150° C (90° to 240° F) higher blade metal temperatures than conventional superalloys.

Prealloyed powder superalloy disks will be stronger and cheaper to fabricate. The use of near-net-shape, hot, isostatic pressing of powder superalloys can reduce starting material to less than half that of standard cast, forge, and machine processing. Currently, in an intermediate step, powders are hot-pressed into simple shapes, which are then forged.

More oxidation resistant, abradable turbine-seal materials are now being readied for application; for example, abradable seals that can reduce turbine tip clearances up to 70 percent. Later, the use of ceramics and low-expansion alloys may allow still smaller clearances.

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TABLE I. - BENEFITS OF MATERIALS FOR TURBINE ENGINES

Component	Material	Pay-offs
Fan blades	Composites	More efficient, lighter, lower cost
Combustor	Oxide dispersion-strengthened superalloys	Stronger, more oxidation resistant
Turbine airfoils	Directionally structured superalloys, ceramics	Higher temperature, reduced cooling, increased life
Turbine seals	Abradable alloys and ceramics	Reduced airflow losses, increased efficiency
Turbine disks	Prealloyed powder alloys	Increased rotor speed, reduced cost, lighter

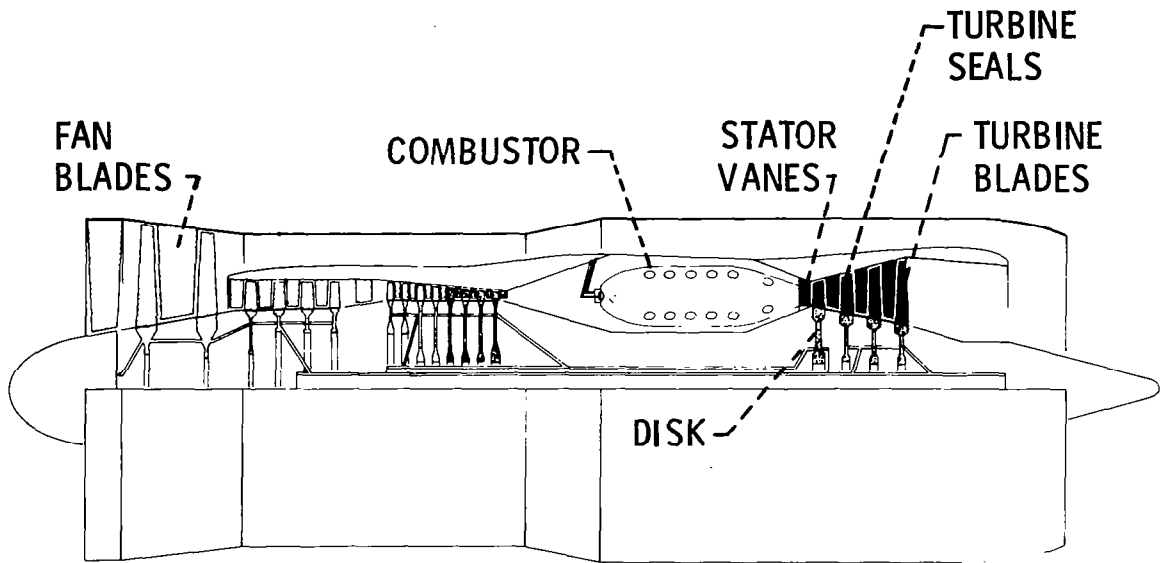


Figure 1.- Engine components studied for application of advanced materials.

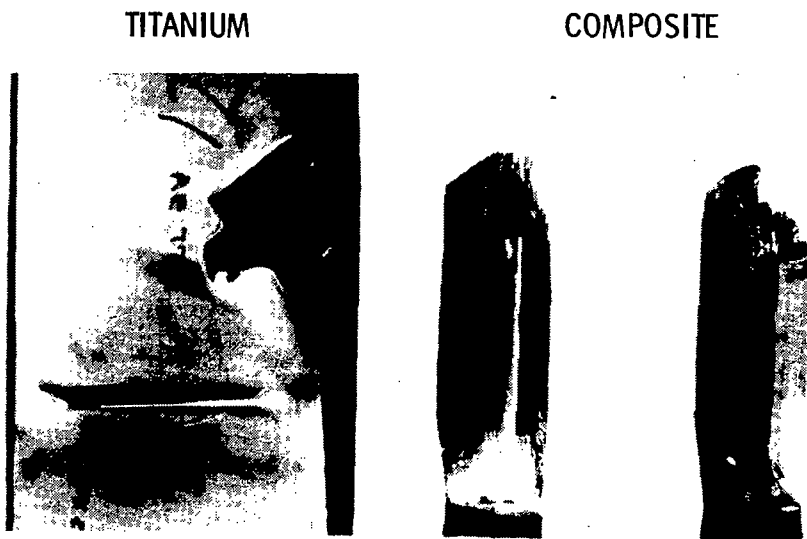


Figure 2.- Bird-ingestion damage to fan blades.

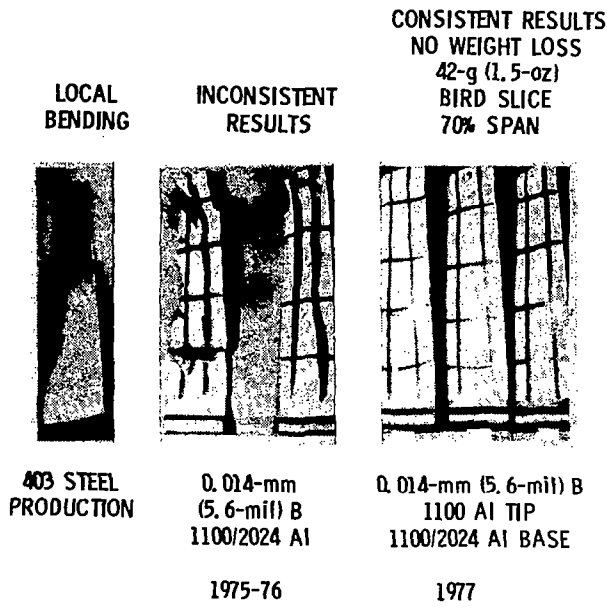


Figure 3.- J-79 stage boron/aluminum blades after starling-impact tests.

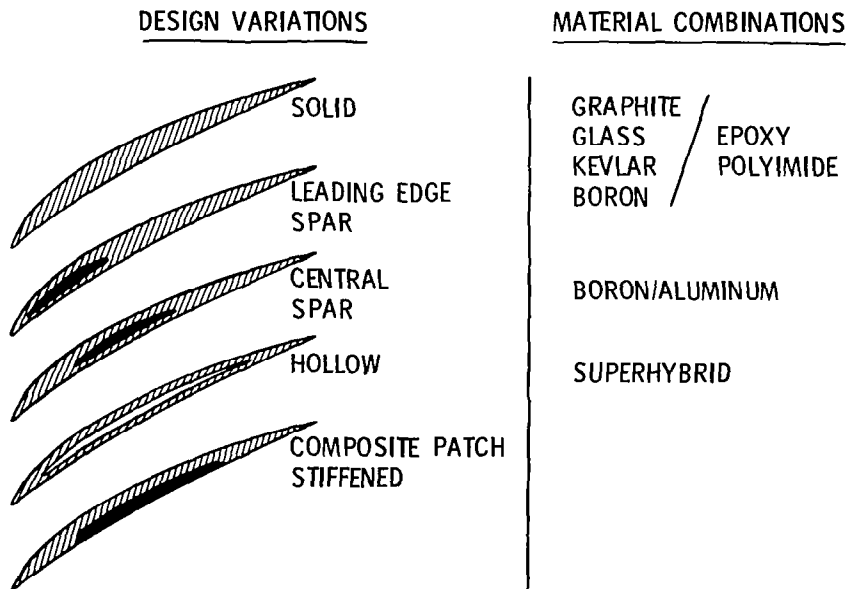


Figure 4.- Composite fan blade materials and design.

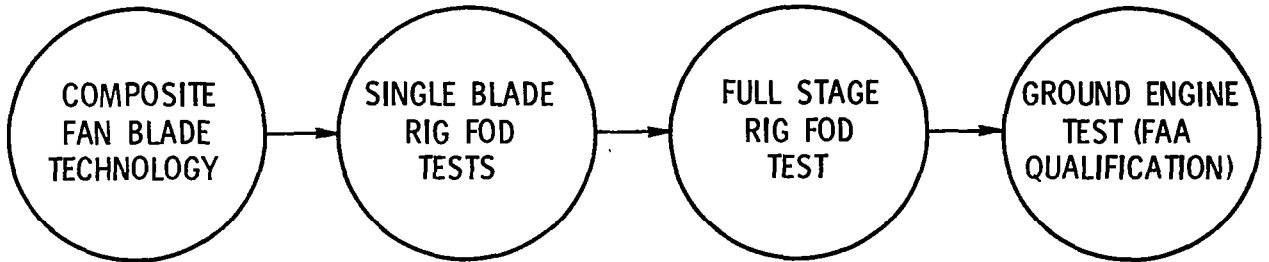


Figure 5.- Procedure for demonstrating composite-fan-blade resistance to foreign-object damage.

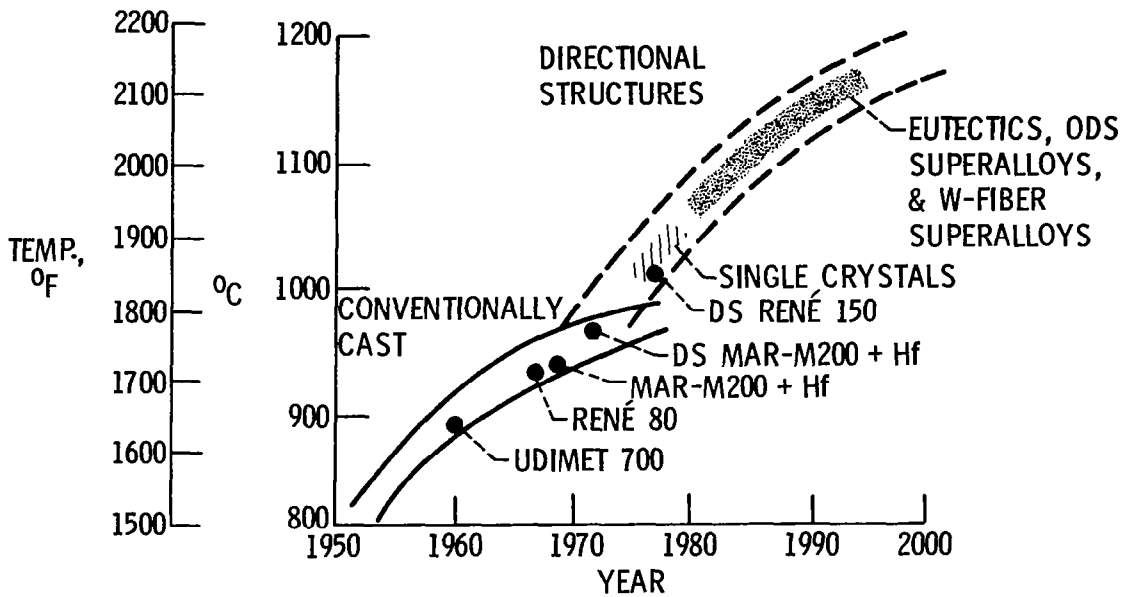


Figure 6.- Use temperatures of turbine-blade materials.

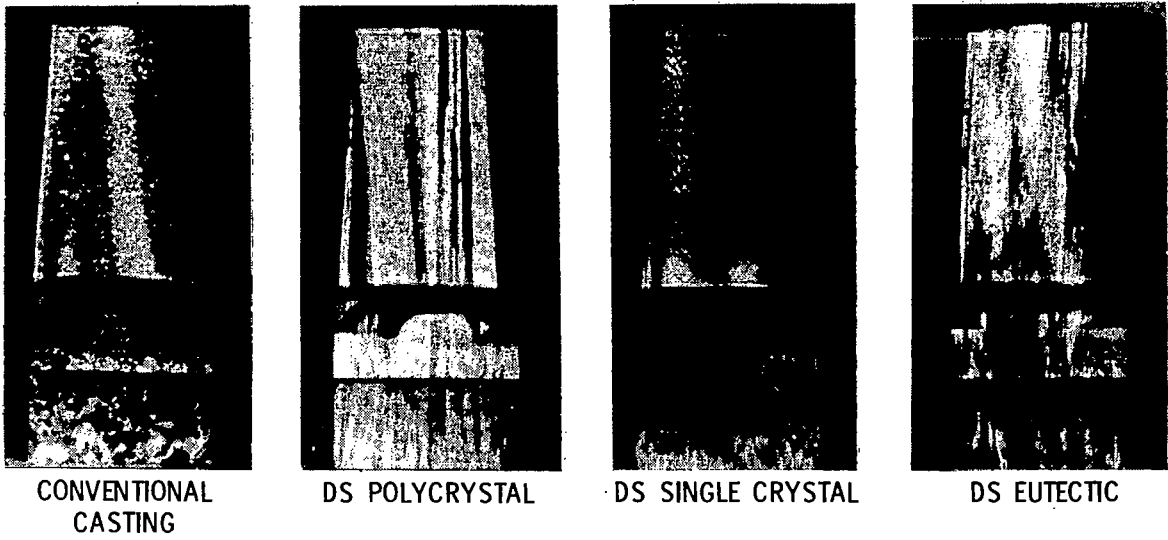


Figure 7.- Trends in turbine-blade material casting methods.

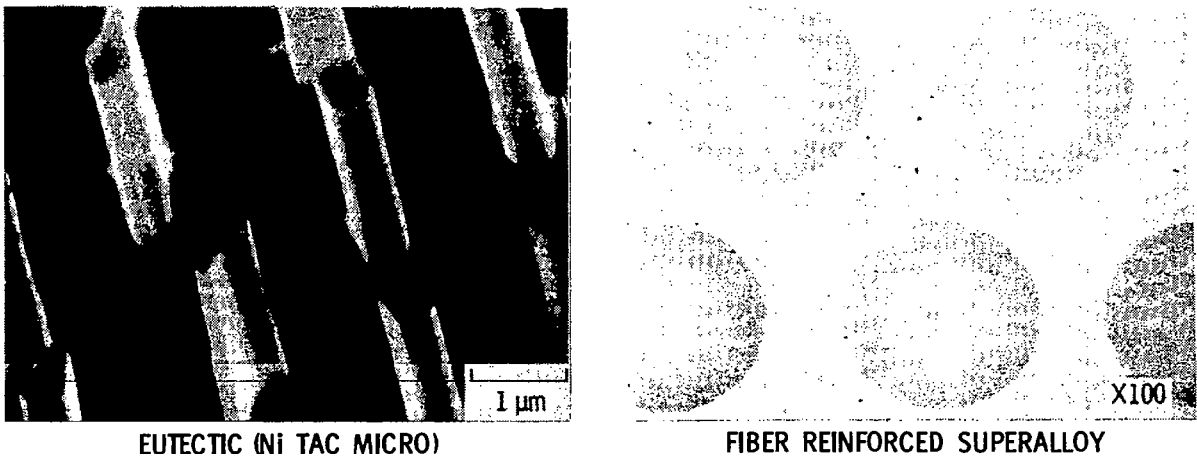


Figure 8.- Directional structures. (Print reduced 30%.)

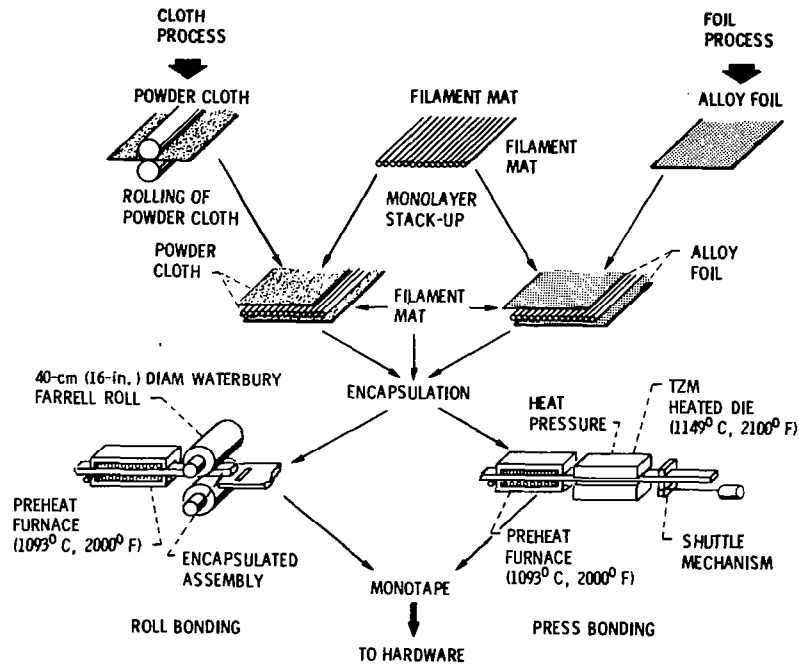


Figure 9.- Manufacture of wire-reinforced superalloy monotapes.

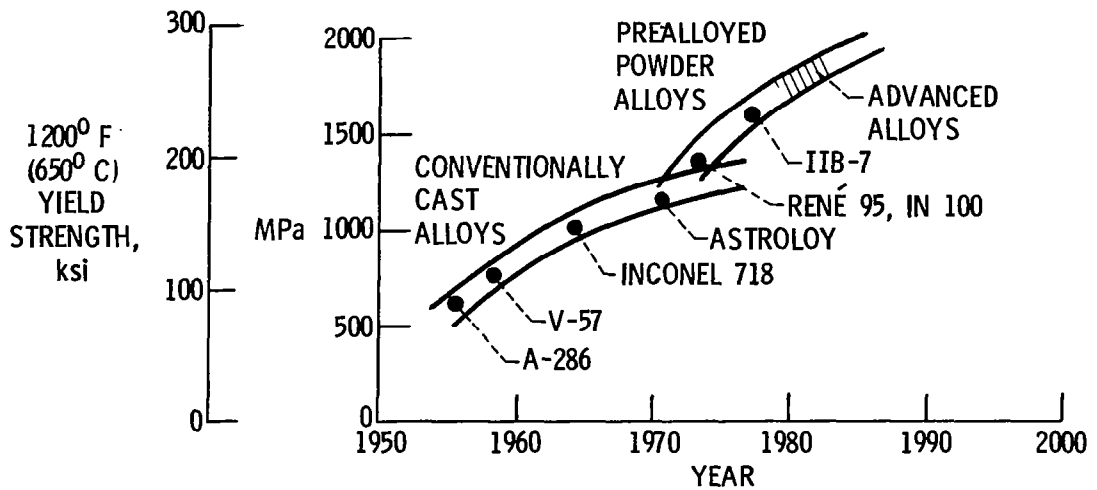


Figure 10.- Strength of turbine disk alloys.

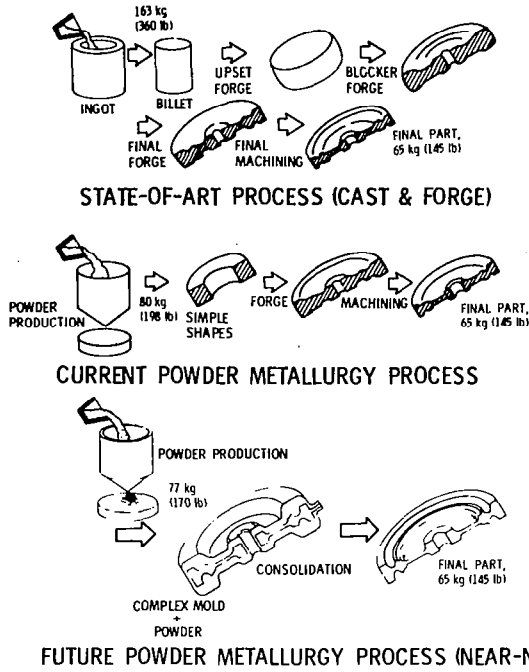


Figure 11.- Turbine disk fabrication processes.

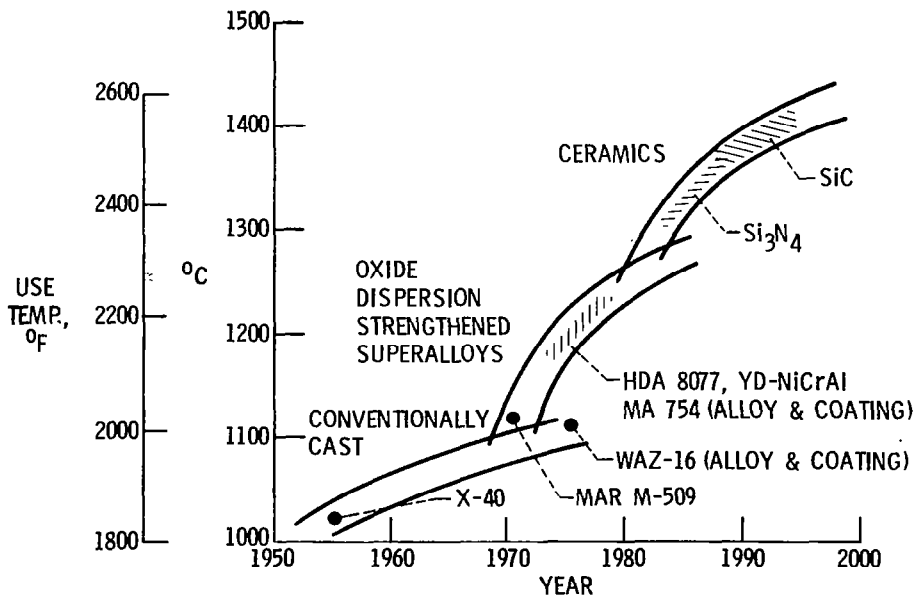
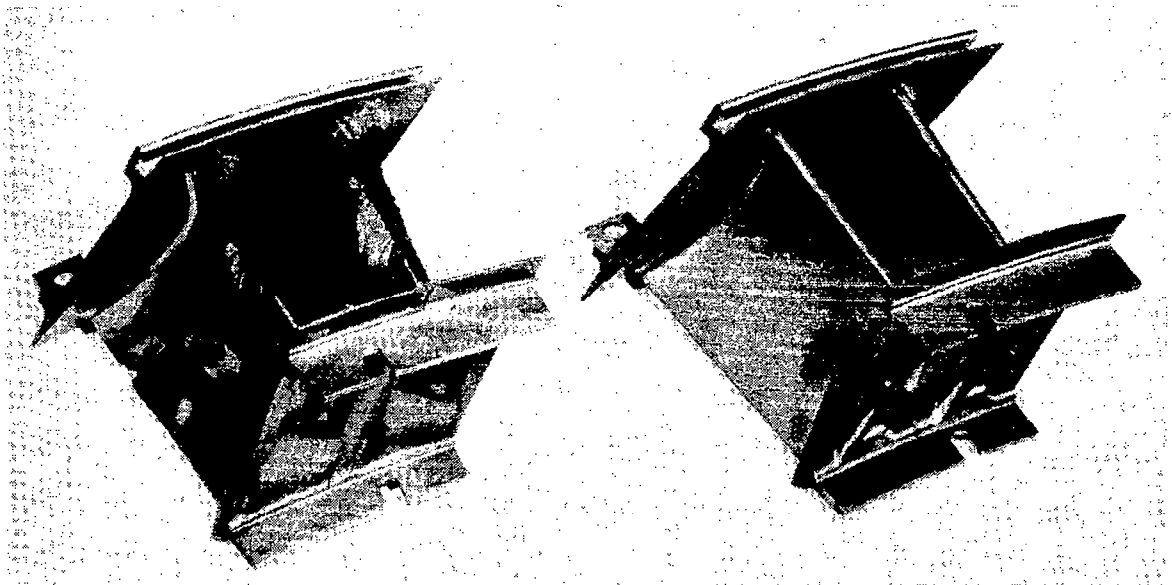


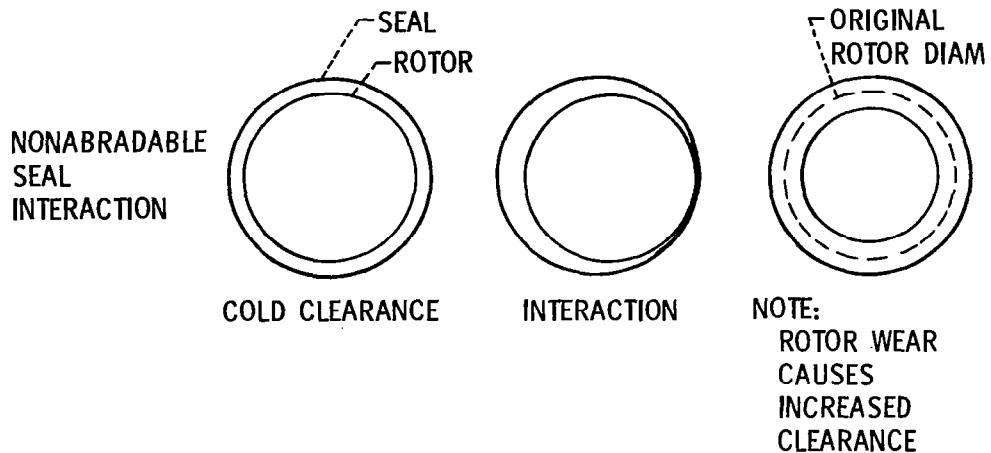
Figure 12.- Predicted higher use temperatures of ODS superalloys and ceramics for turbine vanes.



COOLED MAR-M 509 VANE

UNCOOLED TDNiCr VANE

Figure 13.- Superiority of ODS vanes to conventionally cast vanes subjected to an overtemperature.



REMEDIAL APPROACHES:

- ABRADABLE ALLOYS (NiCrAl)
- NONABRADABLE CERAMICS
- LOW-EXPANSION MATLS

Figure 14.- Schematic of turbine seal and clearance degradation.
(Note: Rotor wear causes clearance to increase 0.25 mm (0.010 in.).)