THE PROCESSING AND TESTING OF A HOLLOW

DS EUTECTIC HIGH PRESSURE TURBINE BLADE

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ABSTRACT

A program to assess the feasibility of Directionally Solidified Eutectic (DSE) High Pressure Turbine (HPT) blades is described. The overall objectives of the program were to define the materials, design and fabrication technology required for the application of eutectic composites in HPT blade components and, through engine testing, to demonstrate their applicability in advance aircraft gas turbine engines.

NiTaC-14B a DSE alloy, has a combination of mechanical properties judged to be superior for turbine blade applications over all other known eutectics. It has a potential temperature advantage of 225°F over the conventionally cast superalloy Rene' 80 and 100°F over the directionally solidified (DS) alloy Rene' 150. A NiTaC-14B blade for testing in a demonstrator engine was designed by significantly modifying the existing DS Rene' 150 blade. The cooling air was markedly reduced and the pitchline airfoil temperature predicted to increase by 100°F. This allowed an effective evaluation of NiTaC HPT blade capabilities under realistic engine conditions.

Hollow HPT blades for test evaluations were cast as close to final external dimensions as practical. Complex internal air cooling passages were cast to size through the use of a new alumina core material/processes developei by General Electric under Air Force sponsorship. A shell mold developed by General Electric was used to form the external blade surfaces. However, because of surface defects in castings made with this mold, the blade was cast oversize to provide sufficient stock for removal of such defects.

HPT blades were finish machined and then subjected to a series of bench tests. The results were combined with blade life analysis results to assess the adequacy of the blade design for engine testing. Subsequently, eight uncoated blades were successfully engine tested.

The program demonstrated that the mechanical properties of the selected NiTaC alloy are very good and that although processing is difficult the manufacture of engine quality hollow DS eutectic blades is feasible.

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Introduction

In the 1970's, several Directionally Solidified Eutectic (DSE) systems were identified as promising blade alloys (1). One such eutectic system, NiTaC, developed by General Electric, consists of aligned, high-strength tantalum carbide (TaC) fibers in a DS gamma-gamma prime, nickel-base matrix. The NiTaC system offers greatly improved rupture strength and other mechanical property improvements over current DS and single crystal alloys. In 1977, the high potential of the NiTaC eutectic system was demonstrated through the successful engine test of solid, uncooled NiTaC-13 low pressure turbine blades. NiTaC alloy development continued concurrently, resulting in significant strength improvements over NiTaC-13 while retaining an excellent balance of ductility, toughness and environmental resistance.

The highest payoff for DS NiTaC eutectics occurs in hollow high pressure turbine (HPT) blade applications. It was expected that the complex internal geometry of HPT blades could be achieved by the cored casting process; however, readily removable cores that could endure the severe environment for casting NiTaC alloys were not available. Consequently, General Electric conducted a core development program under U. S. Air Force sponsorship that identified an injection-molding process for producing the leachable Koralox® alumina core which could survive the casting cycle without deformation or deleterious reactions.

In light of the potential offered by DS NiTaC eutectics, the development of improved NiTaC alloys and the identification of an alumina ceramic that had high potential for fulfilling core requirements, a program was established by the U. S. Air Force to fabricate and evaluate hollow NiTaC HPT blades. The overall objectives were to develop the materials, design, and fabrication technology required for the application of DS NiTaC eutectics in HPT blade components and, through engine testing, to demonstrate their applicability in advanced aircraft gas turbine engines. This ambitious program required the combining of a new alloy system, a new core system and a new internal blade design. To accomplish the objectives, work in the following areas was carried out: 1) microstructural characterization; 2) turbine blade design and analysis; 3) material property data acquisition; 4) core and mold technology development; 5) casting development; 6) machining development; and 7) blade hardware evaluation and engine test. These areas will now be reviewed.

Microstructural Characterization

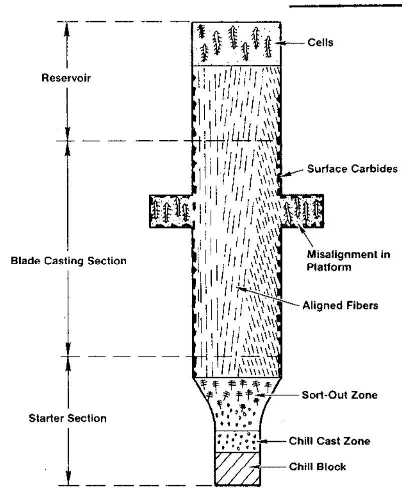

Fig. 1 Schematic Microstructure of NiTaC Blade Casting

NiTaC-14B is a hypereutectic alloy. After an initial chill cast zone, the alloy adjusts to the eutectic composition by the precipitation of coarse carbides in a sort out zone as shown in Figure 1. Aligned fiber growth then proceeds until near the top of the casting where the growth becomes cellular. As noted by Gigliotti and Henry (2) significant chemical segregation occurs throughout the length of the casting, which reduces the rupture strength toward the top of the casting. For this reason, NiTaC blades are normally cast tip down, as shown in Figure 1, to ensure that the best rupture properties are achieved in the airfoil. In addition, a reservoir of metal is placed on top of the casting to limit the amount of chemical segregation, to prevent the onset of cellular growth in the blade dovetail and to ensure that the dovetail has adequate mechanical properties.

Another microstructural aspect of the NiTaC system is that blocky surface carbides precipitate at both the internal and external blade surfaces. These carbides may be up to 30 mils deep and were considered undesirable. Accordingly, the eutectic blade was cast 30 mils oversize so that the carbides on external surfaces could be removed. Analysis and mechanical testing showed that surface carbides on the inside of the blade would not compromise its performance in the planned engine test.

Blade Design and Analysis

Initial studies were performed to determine the potential payoffs of NiTaC-14B and to establish realistic design goals. As a result of these studies, the following goals were set: 1) The pitch line bulk temperature must be more than $100^{o}F$ higher than the existing DS Rene' 150 blade design; 2) The air cooling flow must be significantly less than the Rene' 150 design; 3) The predicted rupture and low cycle fatigue (LCF) life must be equal to or greater than the Rene' 150 design; 4) The external blade configuration must be interchangeable with the Rene' 150 blade design and; 5) The internal design should be of reduced complexity to allow a more rugged core and greater blade castability.

A preliminary configuration for the eutectic blade was designed and analyzed. By reducing the cooling flow by approximately 15% compared to the Rene'150 blade, the bulk temperature of the NiTaC-14B blade was predicted to rise $100^{o}F$. A computer model to calculate the blade natural frequencies for flexural and torsional vibration modes was then constructed using geometric properties of the airfoil cross sections, estimated bulk temperature distributions, and NiTaC-14B elastic modulus data. Analyses were conducted both for laboratory bench test conditions (room temperature and no centrifugal loading) and for engine design point conditions (elevated metal temperatures and centrifugal stiffening effects). Because of some uncertainties in the modeling, the engine test frequencies for the eutectic blade were predicted by comparing the calculated frequencies for the eutectic and Rene' 150 blades with the actual measured bench and engine test frequencies of the Rene' 150 blades. The predicted frequencies were very similar to the Rene' 150 blade; hence, the eutectic blade configuration was considered acceptable for the blade flex and torsional modes.

Enlarged (10X) aluminum models of the pitch and tip section were made to check certain chordwise bending frequencies not predictable by the computer program used. One resonant frequency was found to fall in the engine operating range, and additional stiffening ribs were added to the design to overcome this problem.

The mechanical stresses due to centrifugal loading, gas bending and airfoil untwist were calculated. The higher density of NiTaC-14B over the existing DS alloy resulted in slightly higher predicted stresses in the eutectic blade. Using these predicted stresses, the target bulk metal temperatures required to meet the life goals were then calculated at various airfoil radial spans. Available LCF data indicated that the maximum edge temperatures should be $2100^{o}F$. The preliminary blade cooling design was then tailored to produce the desired temperatures. Having achieved a preliminary blade design, a finite element heat transfer computer program was then run to analyze the blade temperatures in detail. The actual combustor gas temperature profiles obtained during engine tests were used in this analysis. The eutectic blade was predicted to run at essentially the same airfoil root temperature as the Rene' 150 blade, but approximately 100°F hotter in the upper airfoil spans.

To obtain detailed rupture and LCF life predictions, a finite stress analysis program was run, inputting the calculated stresses together with the detailed temperature distributions from the heat transfer analysis. Additional data on elastic constants, thermal coefficients, yield point, stress rupture, creep and thin wall property derates were also entered into the program. The minimum rupture life of the final eutectic blade design was predicted to be approximately 3 times that of the Rene' 150 blade.

The limiting LCF location was calculated to be at the 80% span leading edge nose hole with a life equivalent to the Rene' 150 blade. Furthermore, the Rene' 150 blade was calculated to be limiting in HCF, LCF, and rupture all at the 15% airfoil span; whereas the eutectic blade was HCF limited at the 15% span, LCF limited at the 80% span, and rupture limited at the 50% span. Thus, the eutectic blade was a more balanced design and should have greater capability since it avoids possible interaction of HCF, LCF, and rupture at the limiting life locations.

In summary, the eutectic blade was designed to require 38% fewer film cooling holes, use 15% less cooling air, operate at 110°F higher pitchline bulk temperature and have equivalent LCF capability and 3 times the rupture life of the DS Rene' 150 blade. Were the comparison made with a conventionally cast rather than the DS Rene' 150 design, the advantages of the eutectic design would be even greater, with an estimated 34% savings in overall cooling flow.

Material Property Data Acquisition

To support the design effort, extensive mechanical and physical properties of heat treated NiTaC-14B were measured in laboratory tests. These properties included stress and creep rupture, tensile, HCF, LCF (strain controlled and load controlled), sustained peak LCF, thermal shock and impact. Typical properties for NiTaC-14B are shown in Table I. As can be seen in the longitudinal (casting) direction, mechanical properties exhibited an approximately 225°F superiority over conventionally cast Rene' 80 which is widely used in GE production engines. In the transverse direction, mechanical properties of the two alloys were essentially equivalent. The most surprising result from the testing was the excellent oxidation resistance of NiTaC-14B, which is comparable with some coatings. Additional testing was performed to evaluate the effects on properties of some microstructural defects in castings, microstructural alterations during pre-test thermal exposures, and a selected external overlay coating for environmental protection.

Surface carbides did degrade properties but not drastically. It was calculated that for a 30 mil stress rupture sheet specimen at 18 ksi, bare NiTaC-14B still showed a 230°F advantage over Codep coated Rene' 80, even when taking the greater density of NiTaC-14B into account. The HCF capability was also estimated to be equivalent to current DS or mono alloys. An early test of one blade confirmed that there was more than adequate HCF capability. It was therefore concluded that surface carbides on internal surfaces could be tolerated.

Pre-test thermal exposure did degrade stress rupture and impact properties, but these effects were not unique to eutectics and were not cause for concern. However, the significant degradation in HCF properties due to crack initiation in the overlay coating was judged to present a risk of blade failure during engine testing that was unnecessary to take because NiTaC-14B had adequate oxidation resistance for the planned engine testing. Therefore, the use of the coating was abandoned.

TABLE I. Summary of Round Bar Properties of Solutioned and Aged NiTaC-14B

	Longitudinal	Transverse	CC Rene' 80
Temperature for 100 hours rupture life at 20 ksi	2081°F	1898°F	1840°F
Temperature for 100 hours HCF life (10^7 cycles) at A=00, alternating stress = 60 ksi	1850°F	1410°F	1370°F
Temperature for 100 hours LCF life (10^4) cycles at A=00, alternating pseudo stress = 70 ksi, strain control	1800°F	Est. at least equivalent to R' 80	72°F
Room temperature ultimate tensile strength	205 ksi	155 ksi	148 ksi
Depth of average penetration after 100 hours at 2075°F in Mach 1 dynamic oxidation	--	2.9 mils	24 mils
Depth of average maximum penetration after 100 hours at 1700°F 5 ppm salt	--	10 mils	4 mils

Core and Mold Development

Core Development

Koralox,an all alumina core, was developed at GE by Klug and Pasco (3, 4). The core has a high surface density to resist penetration by the molten alloy and impart a good surface finish to the blade interior. The core also has a porous interior, which allows it to be crushed as the alloy solidifies and shrinks, thereby decreasing the likelihood of casting cracks. In addition, the internal porosity of the core allows it to be readily leached in caustic soda at rates dependent upon the percentage porosity, but at least equivalent to the removal rates of current silica cores.

Much early core development work was done at GE Corporate Research and Development Center and the process was then transferred to Sherwood Refractories, Inc. (SRI) a subsidiary of TRW for scale up. Initially, SRI produced cores of the Rene' 150 blade design and, when tooling was completed, adapted the Koralox process to the production of cores for the NiTaC blade.

The eutectic blade core, very similar to that shown in Figure 2, was designed for airfoil-tip-down castings. The T-bar was used to suspend the core in the mold, and the print outs were used to grip the tip of the core in the mold, as shown in Figure 3. Cores were fired on alumina setters in a covered molybdenum retort which had a piping system for bathing the core surface with dry hydrogen. The retort was placed in a hydrogen furnace and heated at a specified and relatively high rate to 3235°F. After a 2-hour hold time, the furnace was allowed to cool.

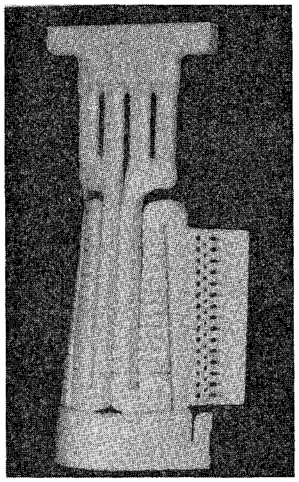

Fig. 2 Typical HPT Blade Core

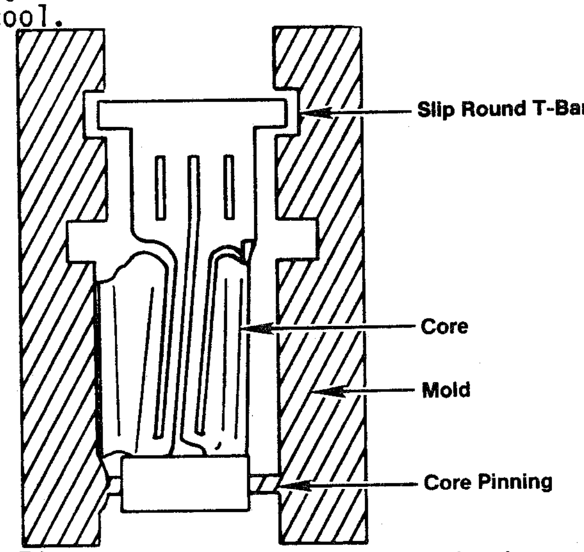

Fig. 3 Schematic of Core Pinning

Three serious problems were encountered: excessive shrinkage, distortion, and cracking. The injection molding formulation for the Koralox core contains alumina and carbon which react at high temperatures (3). If the carbon is prematurely oxidized at low temperatures due to a relatively high dew point or too slow a heating rate, then excessive core shrinkage takes place. As a result of ongoing improvements to ensure a sufficiently dry hydrogen environment, core shrinkage gradually decreased to about 2.0% and became more consistent. However, small process variations affected core shrinkage significantly and further improvements in control are necessary.

It was found that the furnace hearth sagged causing in turn the retorts, setter blocks, and cores to distort. This was significantly reduced by ensuring that the Mo retort always rested on a flat surface in the hydrogen furnace. During firing, it was also found that some of the thin sections of the core slumped under gravity; to alleviate this problem, cross members called tie bars were added to join and mutually support thin sections. These tie bars were added by modifying the core injection die and were removed by grinding after core firing.

Core cracking occurred during firing due to excessive shrinkage and distortion. However, reducing the shrinkage and distortion to acceptable limits also reduced the cracking. As a result of the above modifications, core quality steadily improved.

Blade Wax Injection

Because of the poor core quality produced during the early part of the program, a large proportion of the early castings were scrapped due to core kiss-out. This was attributed to cracking of the cores during injection of blade wax patterns. It thus became imperative to produce wax patterns containing uncracked cores. For this purpose, three methods for producing blade wax patterns with eutectic design cores were evaluated: 1) injection molding at low pressure; 2) pouring molten wax into the wax injection die; and 3) pouring molten wax into a silicone rubber die. The cored blade wax patterns cast in the rubber mold were the most successful because painstaking care had been taken to obtain acceptable wax-pattern wall thicknesses. It was, however, recognized that injection molding was the preferred technique and refinement continued until a sufficient number of satisfactory patterns were eventually produced. Wax patterns of the starter and reservoir sections were then added to the injected blade wax pattern, as shown in Figure 1.

Shell Mold Fabrication

The shell molds developed at GE for casting DS eutectics were made of silica-bonded alumina. The mold construction was of two inner (or face coats) and four outer coats using coarser particles (5). The placement of the core within the mold required attention to the difference in thermal expansion behavior of the mold and core. Figure 4 shows a schematic of dilatometer traces of a Koralox core and an alumina base mold. The core material behaves essentially as fully dense alumina. However, the mold undergoes a net contraction as it is heated between about 1800°F and 2800°F. Core placement and pinning must allow for this difference in thermal behavior in order to properly locate the core in the casting. Thus, the core pinning was designed to allow slippage between the mold and core as in Figure 3. The core tip was clamped by the mold, and pockets were created in which the T-bar could slide. After preparation of the green mold, it was dewaxed by microwave heating. The cored mold was then fired to 1832°F for 2 hours. Heating and cooling rates during this firing step were controlled to a rate 180°F/hr.

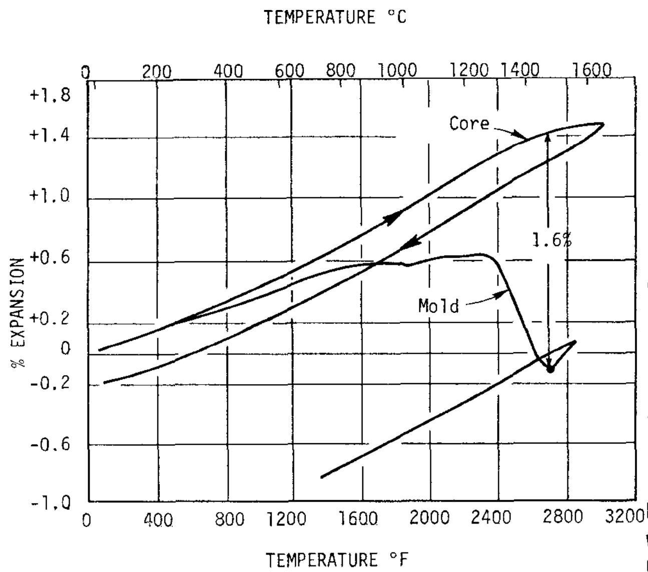

Fig. 4 Core and Mold Expansion

The cored molds were then visually inspected and x-rayed to identify any cores which were improperly pinned or cracked. Mold cracks were repaired with alumina-silica slurry.

Casting Development

The directional solidification furnace was a Bridgman design capable of producing three single blade castings simultaneously. The furnace tank contained 3 high thermal gradient, resistance heated furnaces with individual mold withdrawal units (Figure 5). NiTaC-14B charges were placed in separate shell molded melt cups with a small hole in the bottom sealed with a Ni metal plug. Resistance heated furnaces were placed around each of the melt cups and the assemblies were placed atop the three directional solidification furnaces.

The casting procedure consisted of positioning the molds on pull rods and raising them into the individual furnaces, loading the upper (melting) furnaces with NiTaC-14B charges and closing the chamber. The furnace chamber was evacuated and the individual furnaces heated to 1830°F in vacuo. At this point, the furnace chamber was backfilled with argon-10% carbon monoxide, and the furnace temperatures raised. After holding the mold at temperature to assure conversion to a stable microstructure, the upper furnaces were energized to melt the charge. The molten NiTaC alloy dissolved the Ni plug at the bottom of the melt cup and then quickly filled the cored mold below.

After the charge had melted and filled the mold, the DS furnaces were set for a 3137°F wall temperature and mold withdrawal was initiated. The mold withdrawal rate was held constant through solidification of the airfoil section and then reduced gradually as solidification progressed through the platform, shank, and dovetail of the blade. This rate reduction was done to maintain a constant solidification velocity and carbide fiber alignment. The progression of the solidification front from a section of low cross sectional area to one of high cross sectional area was observed to first reduce and then increase the local solidification rate; the withdrawal rate was decreased to counter this.

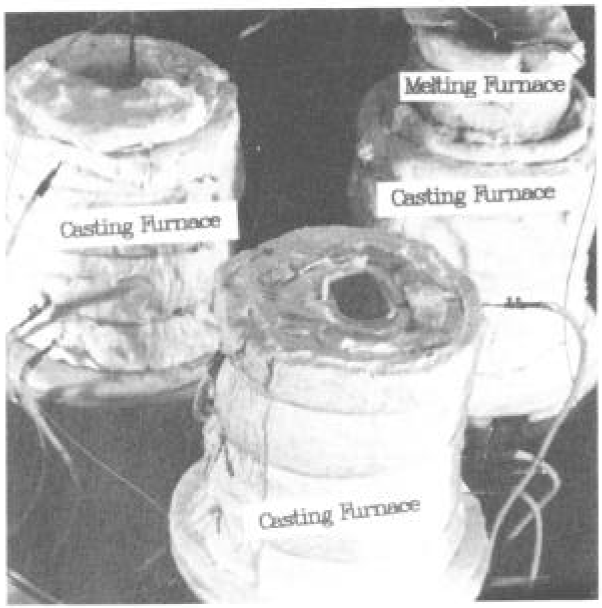

Fig. 5 DS Casting Facility

After casting, the mold was removed, the casting cut, and the core leached in caustic soda solution in an autoclave. After leaching, detailed non-destructive evaluation was performed on each casting to determine acceptability. The evaluations included: 1) internal visual inspection; 2) external visual and fluorescent penetrant inspection; 3) airfoil wall thickness measurements via ultrasonics; 4. microstructural examination for MC-carbide fiber alignment; 5) grain boundary orientation; and, 6) x-ray radiography. A total of 64 castings were examined, of which 17 were considered acceptable for engine testing and 32 were adequate for non-engine component testing.

Machining Development

The first finishing step, removal of excess stock by electro-discharge machining (EDM), was the most critical because internal datum points had to be used to EDM the external airfoil and platform top. During this step, external datum points were established for finish machining of the remaining external surfaces. It was quickly learned that the cores had not been uniformly positioned in the castings, and that it was advantageous to divide the castings into 3 lots to reduce both the number of fixturing setups required and wall thickness deviation from design intent. Establishing fixturing setups for each lot required the use of sophisticated equipment, including a validator and CAD/CAM equipment in an iterative procedure. After each setup was established, using the blade with the average deviation from design intent for the lot, all blades in that lot were machined. This procedure was continued until all airfoils were fully machined.

In the next step, two-piece tip caps were machined from NiTaC-14B, and the blades and tip caps were given a gamma prime solutioning heat treatment. The tip-caps were then brazed in position, inspected, and rebrazed when necessary.

The airfoils and platform tops were then hand ground to finish dimensions, measured ultrasonically for wall thicknesses, etched, and inspected for external defects. During inspection, it was found that many surface carbides were not fully removed which was due, in part, to unequal metal removal from both sides of the airfoil. An unexpected type of defect detected was cracking in the airfoil root on the concave pressure side. Most of the cracks, however, were shallow and were removed by light hand grinding. There was evidence to indicate that these cracks had formed during finishing and not during casting.

Finishing thereafter proceeded more smoothly and included conventional low-stress grinding of the dovetail, EDM of the shank and platform undersides, EDM of cooling holes and special blade features, brazing of balls in the shank to complete the internal cooling system, final inspection, testing of the cooling system in each blade, and shot peening of the dovetails.

Blade Hardware Evaluation and Engine Test

During bench testing, one DSE blade was used to determine nodal patterns during resonance at frequencies in and beyond the engine operating range. The same blade was used to determine strain distributions at all resonant frequencies expected in the engine operating range. Resonant frequencies for the 8 DSE blades selected for engine testing were subsequently determined and showed little scatter. Analysis of the data showed that the vibrational characteristics of the DSE blade were very similar to the Rene' 150 blade. HCF tests of 5 bare DSE blades at the anticipated engine operating temperature were completed prior to engine testing and the results exceeded previous results for the Rene' 150 blade. Hence, these results demonstrated adequate HCF strength of the eutectic blades for engine testing.

Results from nodal pattern and strain distribution measurements were used, in a complex analysis, to determine a single optimum position for the strain gage on all engine test eutectic blades. The analysis also established the stress limits for various resonances that could be expected during engine operation. Bench tests to determine the ultimate-tensile and low cycle fatigue strengths of the blade dovetail also gave satisfactory results.

In early engine testing, data from the strain gages showed that vibratory stresses in the eutectic blades were well below the established limit for the first flex mode. Subsequently, all strain-gage signals were lost and no further stress measurements were possible. Testing was continued with only optical pyrometer measurements of the airfoil surface temperatures on all blades. Engine testing was intermittent and after each test run, all blades were inspected using a borescope.

It was obvious during these inspections that the tips of the eutectic blades were being oxidized, particularly at the trailing edge. Despite this, the engine test was completed as planned.

Testing included 180 accelerated mission test cycles. The total running time was about 184 hours, including 2,290 full thermal cycles with 46 hours at gas stream temperatures within 100^{o}F of maximum operating conditions, and over 2 hours above the design-rated level. The eutectic blades, with a reduced cooling-flow design, operated at temperatures at least 80^{o}F above the Rene' 150 blade.

Post-test visual examination of the eutectic blades revealed that all squealer tips were severely oxidized, especially at the trailing edge. In addition, one blade had a small (0.030") elongated hole through the airfoil wall and another had a series of cracks in the airfoil wall. Microscopic evaluations indicated that the tips ran at a temperature considerably hotter, about 2200^{o}F, than the analytically predicted 2100^{o}F. The excessive temperature was at least partially due to obstruction of tip-cap cooling holes by oxidized surface-carbide particles that were blown from internal cooling cavities. Flow tests of 6 blades after engine testing showed an average loss in tip-cooling flow of about 11 percent, with one blade losing about 37 percent.

Distress of the other two blades mentioned were also surface carbide related. In one blade, oxidation of a cluster of surface carbides through the wall created an elongated hole. In the other blade, the wall was extremely thin, and this combined with surface carbides led to a series of short, jagged cracks. Despite the distress of the eutectic blades, all successfully completed the severe accelerated mission test. Plans have been made to further test two of the blades in another build of the demonstrator engine.

Conclusions

The Rene' 150 blade design was successfuly modified to take advantage of the very good mechanical properties of NiTaC-14B. The measured properties show that the alloy has an approximately 225°F superiority over conventionally cast Rene' 80. A core and mold system suitable for casting NiTaC-14B was developed but further improvements in control of core firing and core location during casting are required. The casting procedure was refined to provide in-situ melt/pour and to ensure the requisite aligned fibers in the blade airfoil and dovetail. Finish machining operations were also successfuly developed. The successful engine test demonstrated the improved performance provided by NiTaC-14B in the HPT blade application.

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