DESIGN OVERVIEW OF FIBER-REINFORCED SUPERALLOY COMPOSITES FOR THE SPACE SHUTTLE MAIN ENGINE

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Abstract

This preliminary design study evaluated the potential of fiber-reinforced superalloys (FRS) for hot-section components of Space Shuttle Main Engine turbopumps. Emphasis was placed on uncooled turbine blades, with a more limited evaluation of FRS turbine stator vanes. The study included FRS properties evaluation, current structural design capability, and preliminary design and structural analysis. In addition, key technology needs were identified, and a plan was generated to develop operational hardware for advanced versions of the SSME. Certain features of the program fell under the constraints of Federal Regulation 22 USC 2278, and will not be discussed in this paper.

Based on projections of design properties for FRS composites comprising 50 volume percent of W-4Re-0.38Hf-0.02C wire filaments in a ductile superalloy matrix, it was concluded that FRS turbine blades offer the potential of significant improved operating life and higher temperature capability over the MAR-M-246(Hf) (DS) blades currently used in the SSME.

A technology plan was devised to bring an FRS turbine blade to a state of operational readiness. It was recommended that the first priority in future work should be placed on acquiring an adequate design data base for tensile, fatigue, thermal shock, and environmental behavior of the FRS composite.

Introduction

Requirements for improved performance and longer life in advanced, liquid propellant rocket engines have focused attention on the potential benefits of composite materials for high-temperature components of the turbines. Space Shuttle Main Engine (SSME) turbine blades (Fig. 1) are currently replaced after about 5000 seconds operation because of fatigue, and even more severe thermal and aerodynamic environments are projected for advanced versions of oxygen/hydrogen engines. It is for this reason that a study program was activated to explore the application of filament-reinforced superalloys (FRS) to hot-section elements of an advanced oxygen/hydrogen engine. The first-stage blades of the high-pressure fuel turbine were chosen as the reference system, and a preliminary design was undertaken based on high-strength tungsten alloy filaments in a ductile superalloy matrix. A final report for the program (Ref. 1) is available from NTIS, Springfield, VA.

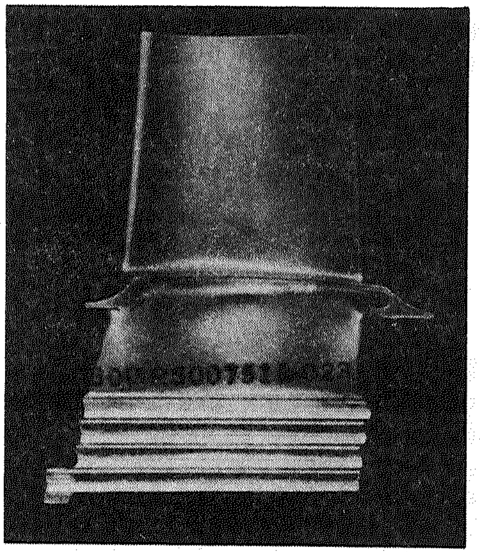

Fig. 1. Present SSME Blade Configuration for First-Stage High-Pressure Fuel Turbopump

Technical Issues

Historically, rocket engine materials have been drawn from an alloy pool developed for use in the airframe and air-breathing turbine industry. This has also been the case for composite materials, at least during the early developmental stages of composite rocket engine hardware. However, it is important to recognize that significant differences exist between the operating and design requirements for rocket engine turbines and those of their counterpart aircraft gas turbines. As can be seen from Table 1, rocket engine turbines may operate at considerably higher

Table 1. Comparison of Operation Characteristics Between Representative Rocket Engine and Aircraft Gas Turbines

ITEM	ROCKET ENGINE TURBINES	AIRCRAFT GAS TURBINES
FUEL	HYDROGEN OR METHANE	PETROLEUM DISTILLATE
OXIDIZER	OXYGEN	AIR
OPERATING RANGE, RPM	36,000 TO 110,000	15,000
BLADE TIP SPEED, FT/SEC	1,850	1,850
HORSEPOWER/BLADE	630	200 TO 400
TURBINE INLET TEMPERATURE, F	1,600 TO 2,200	2,600
HEAT TRANSFER COEFFICIENT, BTU/FT^2-HR-F	54,000	500
THERMAL START/STOP TRANSIENTS, °F/SEC	32,000/7,000	100
ENGINE STARTS	55 TO 70	2,400
OPERATIONAL LIFE, HOURS	7.5 TO 100	8,000

temperature transients that produce higher temperature gradients and thus higher thermal fatigue strains. On the other hand, compared to aircraft gas turbines, rocket engine turbines design lifetimes are much shorter--in the vicinity of 10 hours versus thousands of hours. Thus, for rocket engine turbine materials, one is more interested in short-time tensile strengths; high-thermal strain, low-cycle fatigue; and high mean stress, high-cycle fatigue, but less interested in long-time creep strength and lower mean stress, high-cycle fatigue, which are of greater concern for aircraft gas turbines.

The high operating speeds of the SSME turbine (36,000 rpm) and the alternating bending loads imposed as turbine blades revolve past the stator nozzles lead to an expected fatigue life of the order of 10^8 cycles for the MAR-M246(Hf)(DS) blades presently used in the SSME turbine, so that the blade life is fatigue limited. It is a matter of policy to inspect all turbine blades at frequent intervals and to refit the turbine with new blades after about 5000 seconds (1.4 hours) of operation.

Rocket engine turbine materials are not exposed to sulfidation, and, because of the short times of operation, oxidation is less of a concern than in aircraft gas turbines. However, since the SSME turbine is in reality a hydrogen-rich steam turbine, there is a potential for hydrogen environmental embrittlement (HEE) when components are exposed to the high-pressure hydrogen fuel. This factor must also be considered in the selection of matrix alloys for the fiber-reinforced superalloy composites.

Currently, there are some quite sophisticated efforts under way to extend the functional capabilities of materials for aircraft gas turbines. Examples include the production of turbine blades from single crystals, from rapid solidification process (RSP) superalloy powders, directionally solidified eutectic (DSE) superalloys, oxide dispersion strengthened (ODS) superalloys, and fiber-reinforced superalloys (FRS). Fiber-reinforced superalloys have the potential for the highest strengths at high temperatures of any of these advanced superalloys, but they are in a relatively early stage of development and a number of details must be resolved (e.g., reaction and interdiffusion between reinforcing wire and matrix, reaction of reinforcing wire and matrix with environment, thermal fatigue behavior, and details of design and fabrication). Their higher density, particularly when tungsten is used as the reinforcing wire (and tungsten has been the most popular and highest strength reinforcing wire explored to date) is also a matter to be considered, particularly for turbine blade applications.

Fiber-Reinforced Superalloy Data Base

The FRS materials system selected as the baseline for this study was based on high-strength W-4Re-0.38Hf-0.02C wire filaments coupled with a high ductility superalloy matrix such as Waspaloy, Incoloy 903, FeCrAlY or type 316 stainless steel. Since experimental properties data for these specific composite systems are limited, it was necessary to project design properties through rule-of-mixtures or similar predictive methods.

It must be understood, therefore, that the properties cited in this paper are, for the most part, predicted properties and have yet to be substantiated by appropriate testing.

Recent investigations (Ref. 2-5) of fatigue behavior of composite materials indicate that when the strength of the fiber is significantly greater than that of the matrix, then both low-cycle fatigue (LCF) and high-cycle fatigue (HCF) are controlled by the fibers. Since the operational life of rocket engine turbine blades is expected to be fatigue limited, we selected the strongest known tungsten alloy (W-4Re-0.38Hf-0.02C) as the reference fiber material upon which the projected properties data were based.

The considerations for selecting the matrix material for the FRS blade included:

1. Compatibility with the environment, e.g., hydrogen or hydrogen/steam
2. Compatibility with tungsten wire (fiber degradation)
3. Bond strength between the reinforcement and matrix
4. Thermal fatigue resistance
5. High-cycle fatigue behavior

In the presence of hydrogen, particularly at high pressure and at moderate temperatures, the ductility and notch strength of susceptible alloys can be degraded and crack growth increased if the alloy is subjected to inelastic strain at the time of exposure. This effect has become known as Hydrogen Environment Embrittlement (HEE), and was one consideration in selection of matrix alloys for the fiber-reinforced superalloy systems.

Metallurgical compatibility between matrix and reinforcing filament requires a composite between two opposing requirements. On the one hand, a strongly bonded interface is desirable to accommodate transfer and distribution of load within the composite structure; on the other hand, excessive diffusion of matrix alloying elements can degrade or embrittle the reinforcing fiber. Fiber degradation can be an important factor at operating temperatures above 980 C (1800 F) and for exposures greater than a few hundred hours; it is less of a factor, however, for operational exposures below 100 hours, as is the case for rocket engine applications.

Matrix alloys also play an important role in thermal fatigue, where the ductility of the matrix and its ability to accommodate plastic strain can govern thermal fatigue behavior of the composite (Ref. 6). The degree of mismatch between thermal coefficient of expansion of matrix and fiber is a key factor in thermal fatigue, since this will establish the internal strain at the matrix/fiber interface.

Based on the foregoing selection criteria, five materials were considered as candidate matrix materials. These were Incoloy 903, FeCrAlY alloy, 316L stainless steel, Astroloy, and Waspaloy. Projected design-minimum mechanical properties of these materials are listed in Table 2, and comparative thermal expansion curves are shown in Fig. 2. It is projected that the high-cycle fatigue and low-cycle fatigue behavior of the fiber-reinforced superalloy composite will be governed by the W-Re-Hf-C wire, and that the thermal fatigue behavior will be governed by the properties of the matrix. In this respect, it is desirable to have a ductile matrix material whose thermal expansion is near that of tungsten. The advantage of having ductile matrix materials is twofold: (1) to accommodate the microscopic isothermal strain generated from the differential thermal expansion coefficients between the fiber and the matrix and (2) to accommodate the macroscopic thermal strain generated by the transient thermal gradients during engine start and shutdown.

In Fig. 3 and 4, projections have been made of tensile and specific tensile strengths of candidate fiber-reinforced composite systems based upon incorporation of W-4Re-0.38Hf-0.02C fiber in various superalloy matrix alloys. In all cases, 50 volume

Table 2. Projected Design-Minimum Properties for Candidate FRS Matrix and Reinforcement Materials*

MATERIAL	TEMPERATURE		F_{ty}		F_{tu}		ELONGATION, PERCENT	REMARKS
	°C	°F	MPa	ksi	MPa	ksi		
INCOLOY 903	-195	-320	930	135	1200	175	16	ADJUSTED FOR EXPOSURE TO HYDROGEN-STEAM ENVIRONMENT
	20	70	635	92	930	135	16	
	700	1300	480	70	620	90	8	
	845	1550	70	10	100	15	15	
	1090	2000	14	2	35	5	15	
316 STAINLESS STEEL	-195	-320	290	42	1070	155	40	NO SIGNIFICANT DEGRADATION IN HYDROGEN-STEAM ENVIRONMENT
	20	70	170	25	480	70	40	
	845	1550	35	5	110	16	38	
	1090	2000	14	2	30	4	60	
WASPALOY	-195	-320	1170	170	1550	225	10	ADJUSTED FOR HYDROGEN ENVIRONMENTAL EFFECTS
	20	70	1000	145	1240	180	12	
	370	700	930	135	1200	175	6	
	845	1550	275	40	510	75	23	
	1090	2000	35	5	70	10	30	
ASTROLOY	-195	-320	1030	150	1510	220	15	ADJUSTED FOR HYDROGEN ENVIRONMENTAL EFFECTS
	20	70	965	140	1310	190	15	
	370	700	930	135	1240	180	13	
	845	1550	550	80	760	110	30	
	1090	2000	35	5	70	10	30	
FeCrAlY (25 Cr)	-195	-320	—	--	—	—	—	EFFECTS OF HYDROGEN ENVIRONMENT UPON MECHANICAL BEHAVIOR ARE UNKNOWN
	20	70	240	35	410	60	10	
	845	1550	25	4	50	7	60	
	1090	2000	7	1	8	1.5	100	
W-Re-Hf-C (Wire)	-195	-320	--	--	—	—	--	PROPERTIES ESTIMATES BASED ON LIMITED DATA
	20	70	--	--	2750	400	4	
	845	1550	--	--	2060	300	4	
	1090	2000	--	--	1860	270	4	

* SEE FIGURE 2 FOR THERMAL EXPANSION DATA

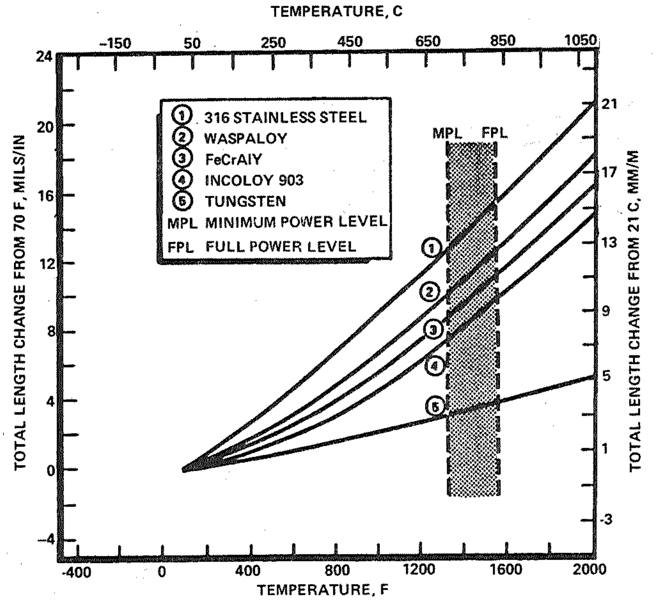

Fig. 2. Comparisons of the Thermal Expansion of Candidate FRS Materials

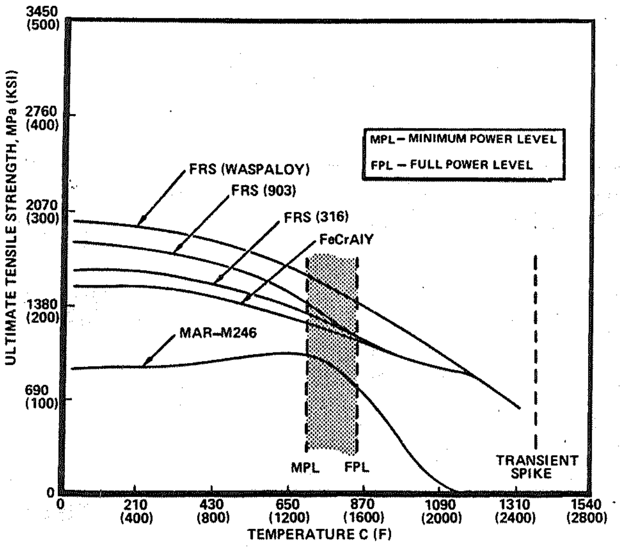

Fig. 3. Projected Tensile Strengths of Candidate FRS Composites

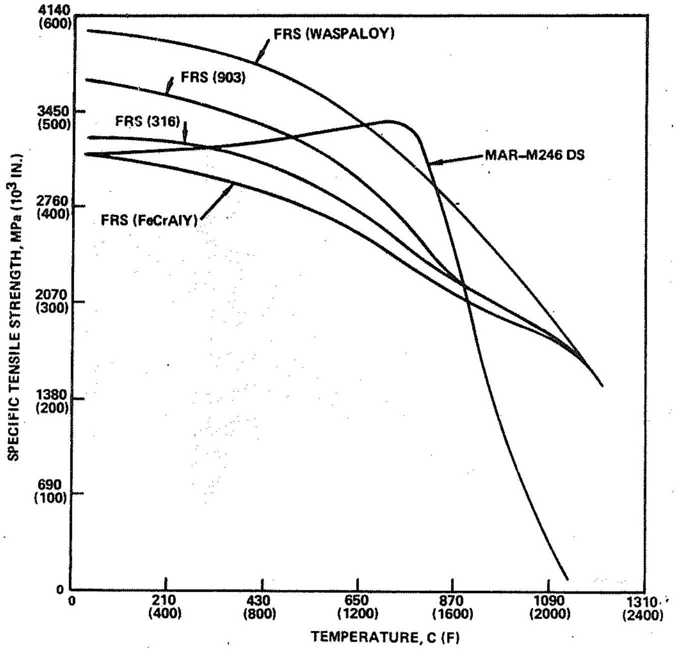

Fig. 4. Projected Specific Strengths of Candidate FRS Composites

percent of the tungsten alloy has been assumed. It will be noted that in all cases, an advantage in tensile strength is apparent over the MAR-M246(DS) blade material currently used in the SSME turbines. When specific strength is considered (Fig. 4), the advantage becomes less apparent below 870 C (1600 F). As a consequence of the higher density of the composite 14 g/cm^3 (0.5 lb/in.^{3}), axial stresses in the denser blade will become higher as a result of centrifugal forces.

Using available fatigue data for FRS composites, a Goodman diagram has been projected (Fig. 5) showing the projected fatigue behavior of a W-Re-Hf-C/Waspaloy

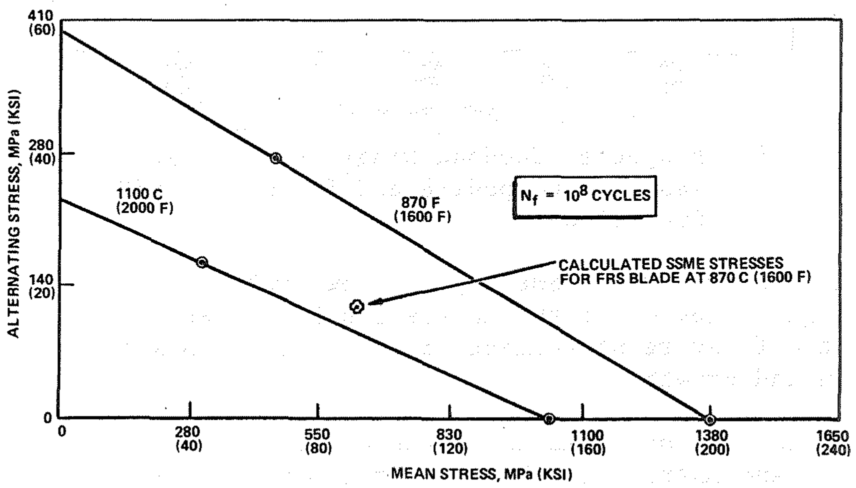

Fig. 5. Projected Goodman Diagram for W-Re-Hf-C/Waspaloy Composite

composite as a function of combined axial and flexural stresses. Curves are projected for 870 C (1600 F) and 1090 C (2000 F) for a fatigue life of 10^8 cycles. In addition, the calculated stresses at the root of the FRS airfoil devised for this application is also shown in Fig. 5. The projected high-cycle fatigue behavior of FRS turbine blades is compared to that of the current MAR-M246(Hf)(DS) alloy in Fig. 6. Fatigue behavior is expected to be influenced, under conditions

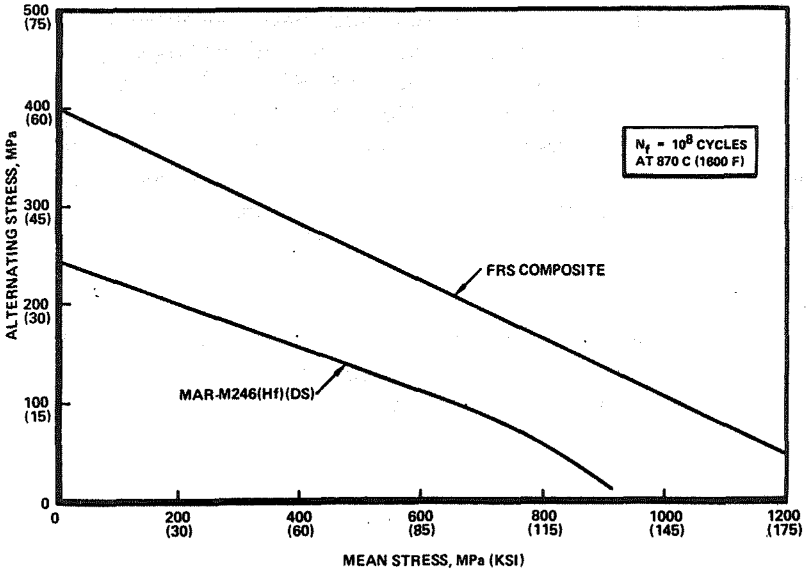

Fig. 6. Projected Goodman Diagrams for W-Re-Hf-C/ Waspaloy Composite and for MAR-M246(Hf)(DS) Superalloy

encountered in the SSME, by the low-cycle (inelastic) fatigue behavior of the matrix and by the resistance of the fiber reinforcement to high-cycle crack initiation and growth.

Because of mismatch in thermal expansion between fiber and matrix, isothermal strain will occur. Figure 7 indicates the strain mismatch that will exist for four candidate matrix alloys, assuming equilibrium at 20 C (70 F). Incoloy 903 would result in the lowest thermal strain mismatch, with Waspaloy and FeCrAlY being about 30 percent higher. Waspaloy, on the other hand, is more ductile than Incoloy 903 and thus may be more capable of withstanding cyclic thermal strain. Although very little strain-controlled, low-cycle fatigue data have been generated for FRS composites, an attempt has been made to project a range of low-cycle fatigue behavior using the Manson-Coffin approach. The results are shown in Fig. 8. The upper and lower limits of the estimated range were derived

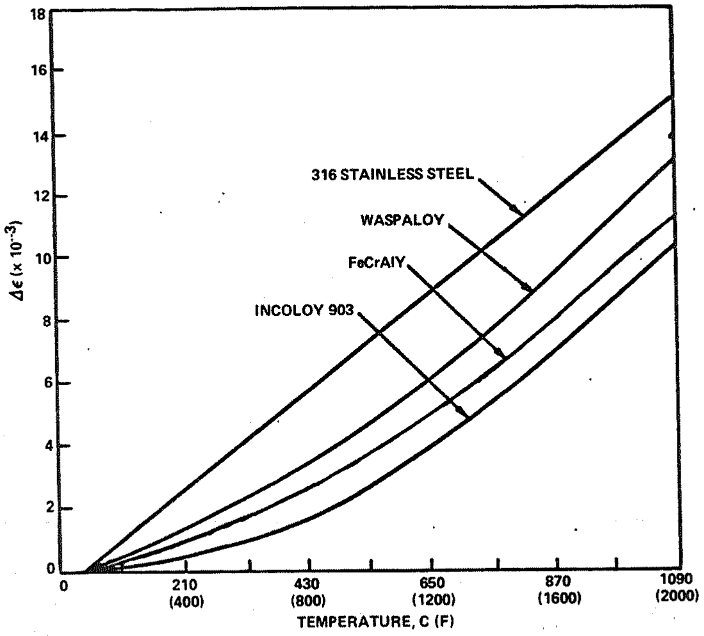

Fig. 7. Thermal Strain at Fiber/Matrix Interface for Candidate FRS Composites

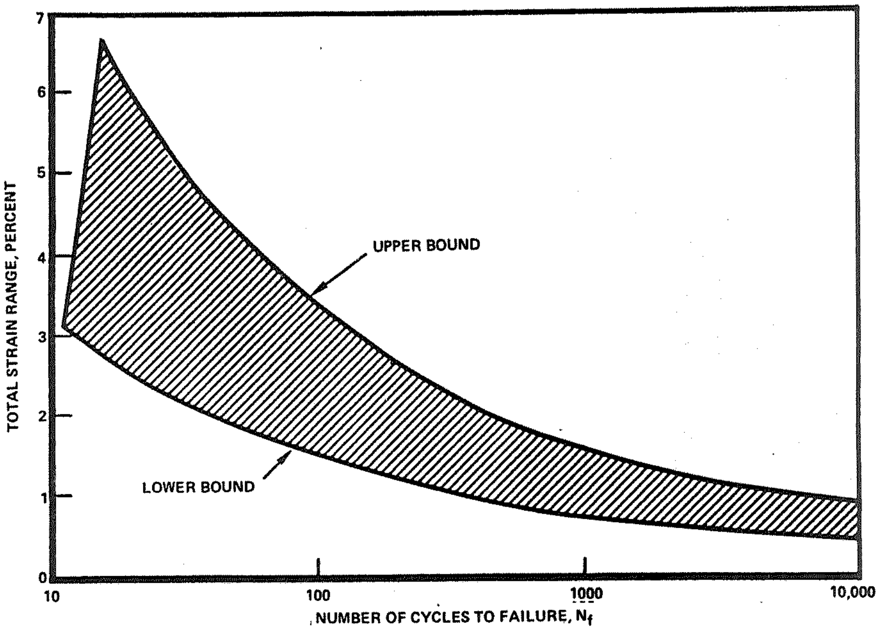

Fig. 8. Low-Cycle Fatigue FRS Composite (1600 F)

for a composite based on 50 volume percent W-Re-Hf-C in a Waspaloy matrix at 1600 F, using the mechanical properties noted in Table 3.

Table 3. Input Data Used in Manson Equation for Estimation of Low-Cycle Fatigue

	ELASTIC MODULUS, GPa(10^6 psi)	TENSILE STRENGTH, MPa(ksi)	DUCITILITY (PERCENT)
LOWER BOUND	255(37)(1)	1379(200)(3)	4(4)
UPPER BOUND	172(25)(2)	1379(200)(3)	23(5)

(1) STAGE I MODULUS (BEFORE MATRIX YIELD)
(2) STAGE II MODULUS (AFTER MATRIX YIELD)
(3) ULTIMATE STRENGTH OF FRS COMPOSITE
(4) DUCTILITY OF W-Re-Hf-C WIRE
(5) DUCTILITY OF WASPALOY

The relatively high thermal conductivity of fiber-reinforced superalloy composites is a distinct advantage in reducing the transient thermal strains that accompany engine start and shutdown. As can be seen in Fig. 9, conductivities of the fiber-reinforced superalloy

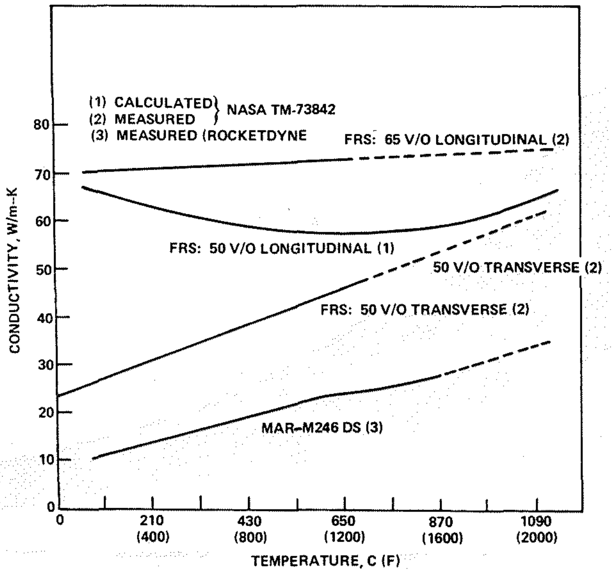

Fig. 9. Thermal Conductivity of FRS and MAR-M246(DS) Superalloys

composites are double that of MAR-M246 at 1600 F. Stress rupture projections are shown in Fig. 10.

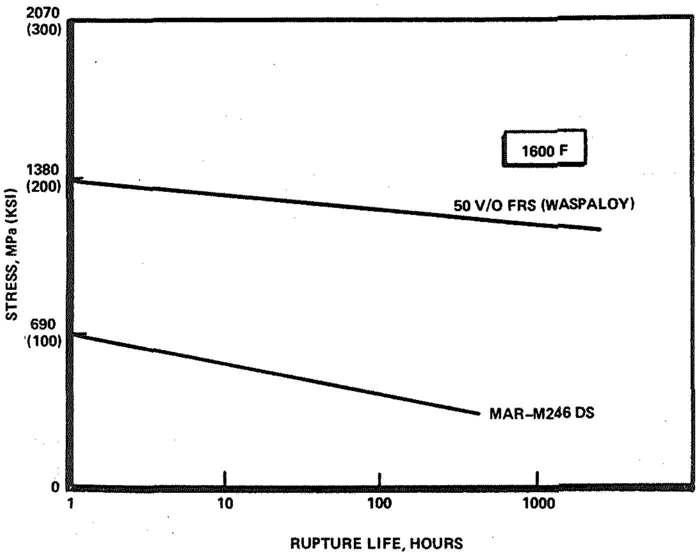

Fig. 10. Stress Rupture of MAR-M246(DS) and FRS Composites

Blade Design

The objective of the fiber-reinforced superalloy blade design and analysis was to develop a preliminary design for an FRS version of an SSME turbine blade. The first-stage blade of the high-pressure fuel pump was chosen as the model, and a composite based on high strength W-4Re-0.38Hf-0.02C wire filaments in a ductile superalloy matrix was selected as the structural system for the blade airfoil. The operating premises upon which the SSME preliminary blade design was based were: (1) that the design properties should be projected from an existing fund of data (no new experimental properties data were generated under this contract) and (2) that the blade should be designed to fit within the current SSME operating parameters and dimensional envelope.

During the course of this program, several fiber-reinforced superalloy turbine blade/disk interface design concepts evolved, including both detachable and integral blade/disk attachments. Although details of blade design and analysis are discussed in the final report for this program (Ref. 1), the constraints of Federal Regulation 22 USC 2278 foreclose any disclosure of these matters to other than citizens of the United States. For this reason, this paper has been limited to a discussion of projected properties. The final report, however, is available to qualified persons through the auspices of NTIS.

Conclusions and Recommendations

The fiber-reinforced superalloy materials system selected as the baseline for this study comprises high-strength W-4Re-0.38Hf-0.02C wire filaments, coupled with a high-ductility alloy matrix such as Waspaloy, Incoloy 903, FeCrAlY or type 316 stainless steel. Experimental properties data for these specific composite systems are limited, and it thus has been necessary to project design properties using rule-or-mixture and engineering judgement. A thorough characterization of design properties, therefore, becomes a key technology issue for any follow-on program. The following are of the most immediate importance:

1. Production of developmental quantities of high-strength tungsten alloy wire (e.g., W-Re-Hf-C)
2. Fabrication of fiber-reinforced superalloy composite stock for testing and evaluation
3. Characterization of the following design properties for fiber-reinforced superalloy composites:
    a. Tensile behavior from cryogenic to evaluated temperatures
    b. Thermal fatigue and high-cycle fatigue properties
    c. Hydrogen-environment embrittlement effects
    d. Stability in hydrogen/water combustion environment

e. Properties of brazed and/or diffusion-bonded joints

f. Thermal shock behavior under SSME start and shutdown

g. Stress-rupture behavior

The operating premises upon which the SSME preliminary design was based were: (1) that the design properties should be projected from an existing fund of data (no new properties data would be generated under this contract) and (2) that the components should be designed to fit within the current SSME operating parameters and dimensional envelope. Specific findings of the effort are summarized below:

1. <u>The short, stubby blade of the SSME high-pressure fuel turbine is well suited for FRS composite application.</u>
2. <u>Design properties, based on projections of existing data, offer significant advantages in both operational life and high-temperature capability for FRS* turbine components.</u>
3. <u>FRS turbine components lend themselves to a variety of advanced earth-to-orbit booster rocket engines.</u>

   The current SSME is a staged combustion cycle engine utilizing hydrogen as a fuel. Other engine systems can involve different fuels (e.g., methane) or other cycles (e.g., gas generator) to heat the working fluid which drives the turbopump. The advantage of FRS turbine blades lies in their capability to withstand exposure to the high temperatures involved in advanced engines, as well as to offer extended operating life.

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*50 volume percent W/Hf-Re-C fiber in a Waspaloy matrix.

4. A plan has been provided to develop the needed technology to create operational FRS turbopump components for advanced versions of the SSME.

   A three-phase plan is visualized to bring an FRS blade to a state of operational readiness. The current study program, which constitutes Phase I, has identified the needed technologies and has recommended a turbine blade as the component for future effort. During Phase II, the needed technologies will be developed. The third and future phase of the projected program will be concerned with component fabrication, system integration, and demonstration through simulated service test-bed hot firings.

Acknowledgements

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