SECOND-GENERATION NICKEL-BASE

SINGLE CRYSTAL SUPERALLOY

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Abstract

Significant increases in high temperature strength capability have been achieved in a second-generation nickel-base single crystal alloy designed for advanced military and commercial turbine airfoil applications. This new alloy, designated PWA 1484, offers a 50°F improvement in metal temperature capability (creep-rupture strength, thermal fatigue resistance, and oxidation resistance) over PWA 1480, the first nickel-base single crystal turbine alloy to enter production. PWA 1484 represents the first use of rhenium in a production single crystal superalloy. The alloy properties have been fully characterized and demonstrate an outstanding combination of high-temperature creep and fatigue strength as well as excellent oxidation resistance. Production processing of single crystal PWA 1484 castings has shown that the alloy has good castability and a wide solution heat treatment range. The superior properties of PWA 1484 have been confirmed through extensive engine testing.

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Introduction

As operating temperatures of gas turbine engines have steadily increased, the demands placed on turbine airfoils have escalated dramatically. To meet these accelerating demands on the capability of high-temperature materials, significant breakthroughs in alloy design and processing have been made (1,2,3).

The directional solidification casting process, pioneered by Pratt & Whitney in the 1960's, has led to the development of a series of columnar grain and single crystal alloys designed for turbine airfoil applications, with temperature capabilities more than 100°F higher than their conventionally cast predecessors. PWA 1480 (4), the first production single crystal turbine airfoil alloy, entered service in 1982 and has successfully accumulated more than five million flight hours in commercial and military engines.

To obtain further improvements in alloy capabilities needed to meet the turbine airfoil requirements for advanced commercial and military engines for the 1990's, alloy development efforts at Pratt & Whitney have been focused on defining a second-generation single crystal alloy (5). The demanding goals established for this program were a 50°F improvement in airfoil metal temperature capability compared to PWA 1480, in an alloy that is microstructurally stable after long-time exposure, and has good castability.

Alloy Goals and Design Approach

The basic design goals established for the second-generation single crystal alloy were as follows:

1. 50°F improvement in airfoil capability relative to PWA 1480
   a. Creep-rupture strength
   b. Coated and uncoated oxidation resistance
   c. Thermal fatigue resistance

2. Other critical properties
   a. Absence of secondary phase precipitation after long-time static and dynamic thermal exposure
   b. Intermediate to elevated temperature high cycle fatigue strength comparable to PWA 1480

3. Ease of processing
   a. Castability equivalent to PWA 1480
   b. Solution heat treatment range greater than PWA 1480

To meet these challenging goals, an extensive alloy development effort was undertaken using the knowledge gained in over twenty years of cast superalloy development (1). It was found that to meet the high-temperature strength goals, a significant increase in refractory metal content compared to the 16 weight percent (w/o) tantalum plus tungsten contained in PWA 1480 was required. These studies also showed that it was necessary to maintain a high volume fraction (60 to 65%) of γ' with a solvus temperature in excess of 2350°F to achieve the strength goals. In these studies, rhenium was found to be an especially potent and necessary solid solution strengthening agent to achieve the required ultra high strength levels. To produce a high volume fraction of γ' precipitate, which was relatively resistant to coarsening at high temperatures and had a high solvus temperature, it was determined that the alloy under development should have at least 5.5 w/o aluminum and a high level of tantalum.

Previous alloy development efforts had determined that raising the refractory content above a critical level, however, could lead to the precipitation of refractory-rich secondary phases such as alpha tungsten, as well as mu or sigma phases. These phases which can form following long-time elevated temperature exposure, robbing the alloy of its prime solid solution strengthening agents, have been observed to compromise alloy properties and thus must be avoided.

To achieve the creep strength goal of a 50°F improvement over PWA 1480, which is a threefold increase in life, while maintaining microstructural stability, a series of alloys was screened at 36 ksi at 1800 and 1850°F to define the optimum balance of the refractory elements: molybdenum, tantalum, tungsten, and rhenium. The alloy with the optimum combination of properties resulting from these screening trials has been designated PWA 1484. The composition of PWA 1484 is compared to that of PWA 1480 in Table I. As shown in the table, PWA 1484 contains 3 w/o rhenium and is the first production single crystal superalloy to employ this element as an alloying addition. To ensure maintenance of microstructural stability at the high (20 w/o) refractory content of PWA 1484, the chromium level of the new alloy was lowered to 5 w/o, compared to 10 w/o in PWA 1480.

Table I. PWA 1484 Composition and Heat Treatment

	Chemistry (weight percent)									
	Ni	Cr	Ti	Mo	W	Re	Ta	Al	Co	Hf
PWA 1480	Bal	10	1.5	-	4	-	12	5	5	--
PWA 1484	Bal	5	-	2	6	3	8.7	5.6	10	0.1

PWA 1484 Heat Treatment: 2400°F (4 hours) + 1975°F (4 hours) + 1300°F (24 hours)

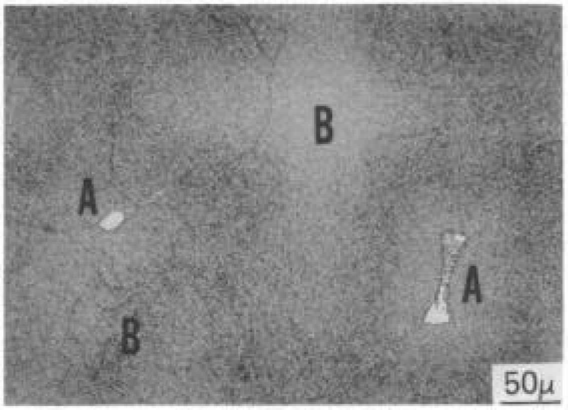
Alloy Properties

Microstructure and Heat Treatment

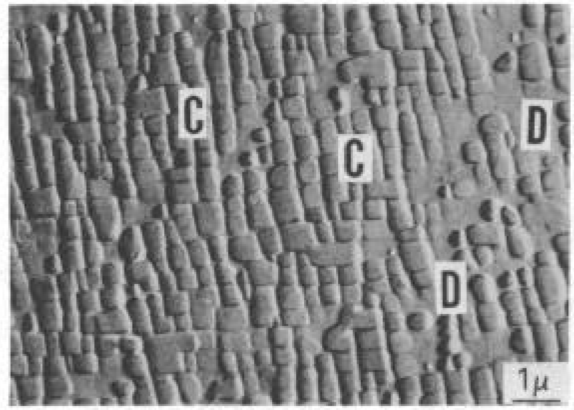
The composition of the new alloy was designed to have a large range between its incipient melting temperature (2440°F) and its γ' solvus temperature (2370°F). The cobalt content of PWA 1484 was increased by 5 w/o relative to PWA 1480 to help expand the heat treatment range, partially offsetting the effect of the reduced chromium. As shown in Figure 1, a nominal 2400°F solution heat treatment for 4 hours results in almost complete solutioning of the coarse as-cast γ' in the alloy and their reprecipitation in a uniform array of fine ($\leq 0.3\mu$) cuboidal particles.

The microstructure of PWA 1484 in the as-solutioned and fully heat treated conditions is presented in Figure 2. PWA 1484 retains a very fine γ' particle size after full heat treatment which is believed to result from rhenium additions that retard γ' coarsening (6).

The heat treatment of PWA 1484, as shown in Table I, consists of a three-step process employing a 2400°F for 4 hour solution heat treatment. This solution heat treatment dissolves the coarse as-cast γ' present in the alloy which is reprecipitated as a fine regular array of cuboidal particles upon controlled cooling from 2400°F. Following the solution heat treatment cycle, a 1975°F for 4 hour cycle is used to bond the coating to the alloy, as well as to produce an optimum γ' size and distribution. To enhance intermediate temperature yield strength, the PWA 1484 heat treatment incorporates a 1300°F for 24 hour age which precipitates ultra fine γ' ($\leq$0.1μ) between the larger particles as seen in Figure 3.

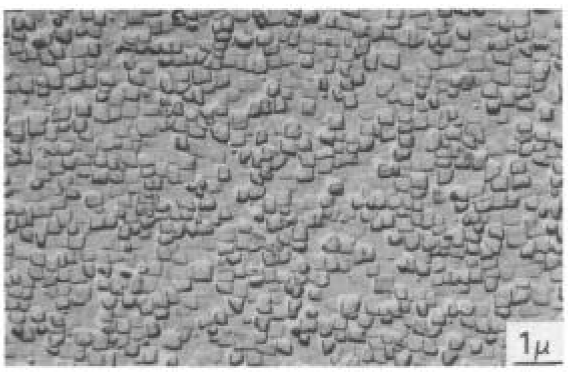


GAMMA/GAMMA PRIME EUTECTICS (A) AND UNRESOLVED GAMMA PRIME PRECIPITATES (B) IN GAMMA MATRIX

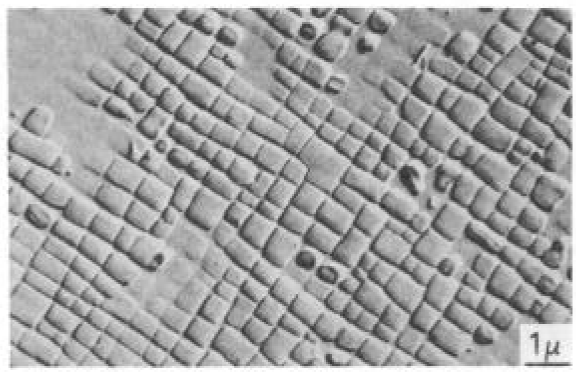


FINE GAMMA PRIME PRECIPITATES (C) IN GAMMA MATRIX (D)

Figure 1 - Typical microstructure of solution heat treated PWA 1484.

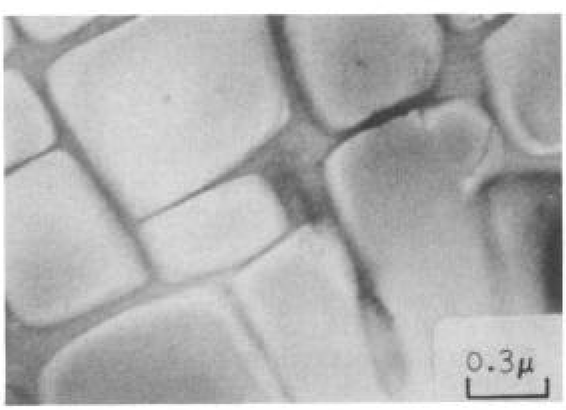


AS-SOLUTIONED 2400°F(4HRS)

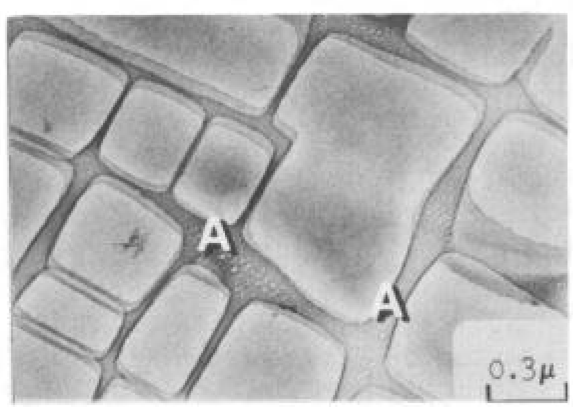


FULLY HEAT TREATED 2400°F (4HRS) + 1975°F (4 HRS) + 1300°F (24 HRS)

Figure 2 - PWA 1484 retains fine γ' microstructure after full heat treatment.



NO AGE

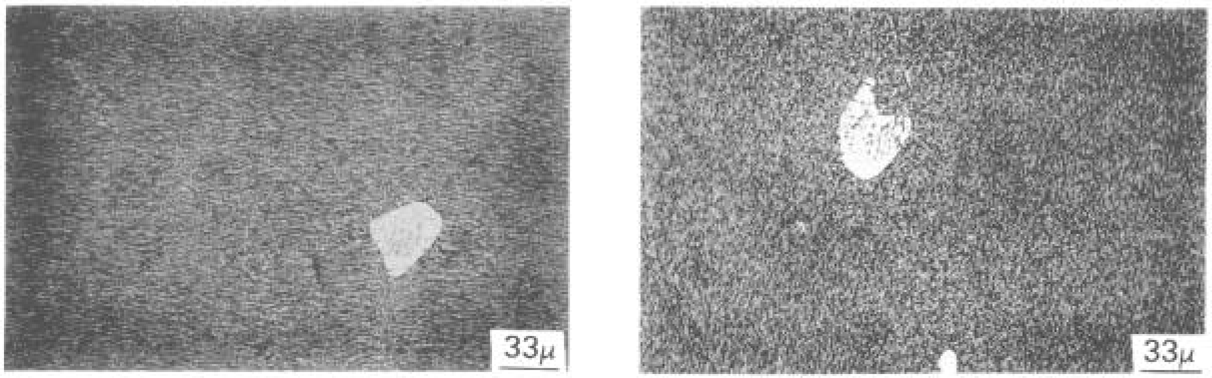


704°C (1300°F) FOR 24 HOURS

Figure 3 - 1300°F aging heat treatment precipitates an additional small volume fraction of ultra fine γ' precipitates (A) in PWA 1484.

Long-Term Microstructural Stability

The PWA 1484 composition was designed to be free of secondary phase instabilities after long-time elevated temperature exposures. Metallographic evaluation of specimens furnace exposed between 1600 and 2000°F for 1000 hours as well as specimens creep tested for up to 2000 hours between 1600 and 2000°F (Figure 4) has confirmed the excellent microstructural stability of the alloy.



FURNACE EXPOSURE AT 1800°F FOR 1000 HOURS

CREEP TESTED AT 1800°F/25 ksi FOR 1997 HOURS

Figure 4 - PWA 1484 microstructure is free of secondary phase instabilities after long-time static and dynamic exposure at elevated temperatures.

Creep-Rupture Strength

Creep-rupture testing of PWA 1484 at 36 ksi indicates that the alloy offers almost a fourfold increase in life over PWA 1480 at this stress, which corresponds to a 70°F metal temperature advantage, easily surpassing the program goal of a 50°F improvement (Table II). At a stress of 36 ksi, PWA 1484 exhibits longer creep and rupture lives when tested at 1850°F than does PWA 1480 in testing at 1800°F, clearly demonstrating that PWA 1484 offers more than a 50°F improvement in creep-rupture capability over PWA 1480. The density of PWA 1484 is 0.323 lb/in^3; and on a density corrected basis, PWA 1484 has a 65°F metal temperature advantage over PWA 1480. Testing at other temperature/stress conditions demonstrates that PWA 1484 offers an even greater improvement over PWA 1480 with advantages in life ranging from 4X at 1700°F/50 ksi to greater than 8X at 2000°F/18 ksi. Comparing the creep strength of the two alloys on the basis of stress for time to 1% creep in 300 hours versus temperature (Figure 5), it can be seen that PWA 1484 retains greater than a 50°F temperature advantage relative to PWA 1480 over a wide temperature range (1500 to >2000°F). Since the initial screening trials, several hundred additional creep-rupture tests have been performed on specimens machined from cast bars, as well as from solid blades, verifying the initial data. These tests have been conducted on specimens from more than a dozen large commercial heats (≥2000 lb).

A study of the effect of cooling rate from the solution heat treatment temperature on strength has shown that the creep-rupture strength of PWA 1484 can be maximized by producing a γ' particle size in the range of 0.25 to 0.35μ (7). This optimum size range can be readily achieved using the full heat treatment cycle for the alloy with a rapid cooling rate from the solution heat treatment temperature, and then applying a 1975°F for 4 hour coating diffusion cycle followed by a 1300°F for 24 hour age.

Table II. Creep-Rupture Data at 36 ksi

	1800°F		1850°F	
	Rupture Life (hours)	Time to 1% Creep (hours)	Rupture Life (hours)	Time to 1% Creep (hours)
PWA 1480	90	36	30	12
Program Goal	270	110	90	36
PWA 1484	350	135	117	45

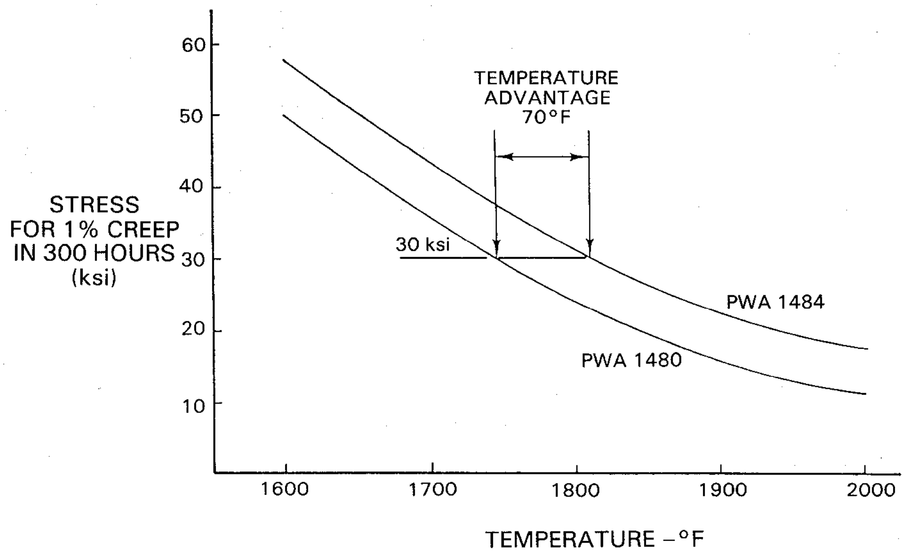


Figure 5 - PWA 1484 exhibits a significant creep strength advantage relative to PWA 1480 over a wide range of temperatures.

Tensile Properties

The tensile properties of PWA 1484 have been extensively characterized in a series of tests between room temperature and 2000°F (Figure 6). The yield strength of PWA 1484 at temperatures below 1200°F is approximately 140 ksi which is similar to that of other single crystal alloys (8). At intermediate to elevated temperatures (≥1400°F), the yield strength of PWA 1484 is superior to most other single crystal alloys. Despite its high yield strength, PWA 1484 exhibits excellent tensile ductility from room temperature to 2000°F (Figure 6) with typical ductilities greater than 12% at all temperatures.

Oxidation and Hot Corrosion Resistance

Burner rig oxidation tests conducted on PWA 1484 at 2100°F, in both the uncoated and overlay coated conditions, indicate that the alloy possesses oxidation resistance even better than that of PWA 1480 which has excellent oxidation resistance. Based on metal recession data (Figure 7), uncoated PWA 1484 specimens oxidize at about half of the rate of PWA 1480 specimens under severe conditions (temperatures ≥2000°F). On the basis of time to 5 mils of metal loss at 2100°F, PWA 1484 demonstrates more than a 60% life improvement over PWA 1480 (Figure 7). Testing conducted between 2050 and 2150°F indicates that PWA 1484 offers a 65°F improvement in metal temperature capability over PWA 1480, surpassing the program goal of a 50°F improvement in oxidation resistance.

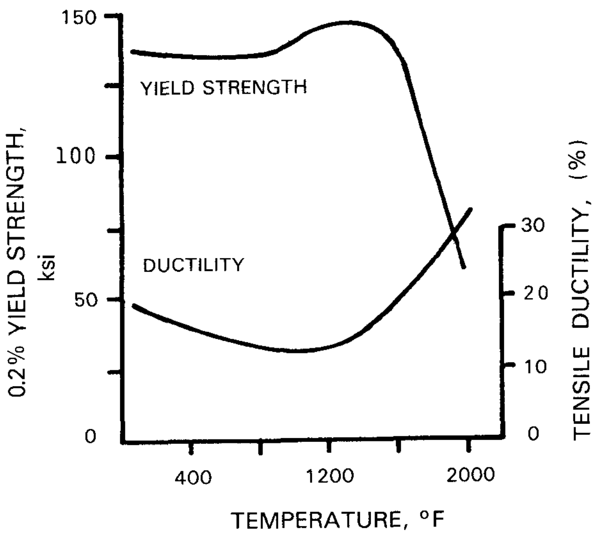


Figure 6 - Tensile properties of PWA 1484.

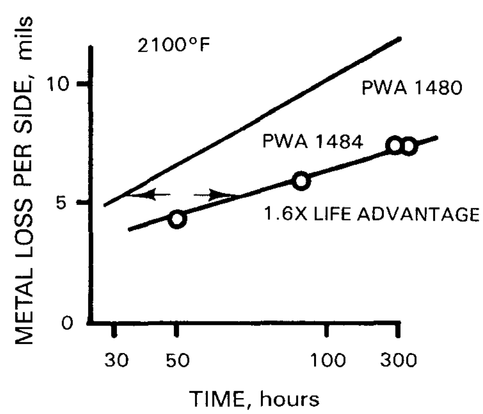


Figure 7 - PWA 1484 uncoated oxidation resistance at 2100°F is superior to that of PWA 1480.

The excellent oxidation resistance of PWA 1484 is attributable to its higher aluminum content compared to PWA 1480, its relatively high tantalum content, and the fact that it does not contain titanium.

In addition to the uncoated tests, a series of burner rig oxidation tests with a NiCoCrAlHfSiY overlay coating were conducted between 2000 and 2150°F. These tests, some of which ran for more than 6000 hours at 2000°F, demonstrated the superior oxidation performance of the overlay coating on PWA 1484, with lives 70% greater than on PWA 1480 (Figure 8). This translates to a 70°F advantage in metal temperature capability over PWA 1480, surpassing the program goal of a 50°F improvement.

The alloy has also been evaluated in a series of ducted burner rig hot corrosion tests using a synthetic sea salt mixture to induce hot corrosion. These tests, which were conducted both isothermally and cyclically, have shown that PWA 1484 has hot corrosion resistance similar to PWA 1480 and other high-strength turbine airfoil alloys.

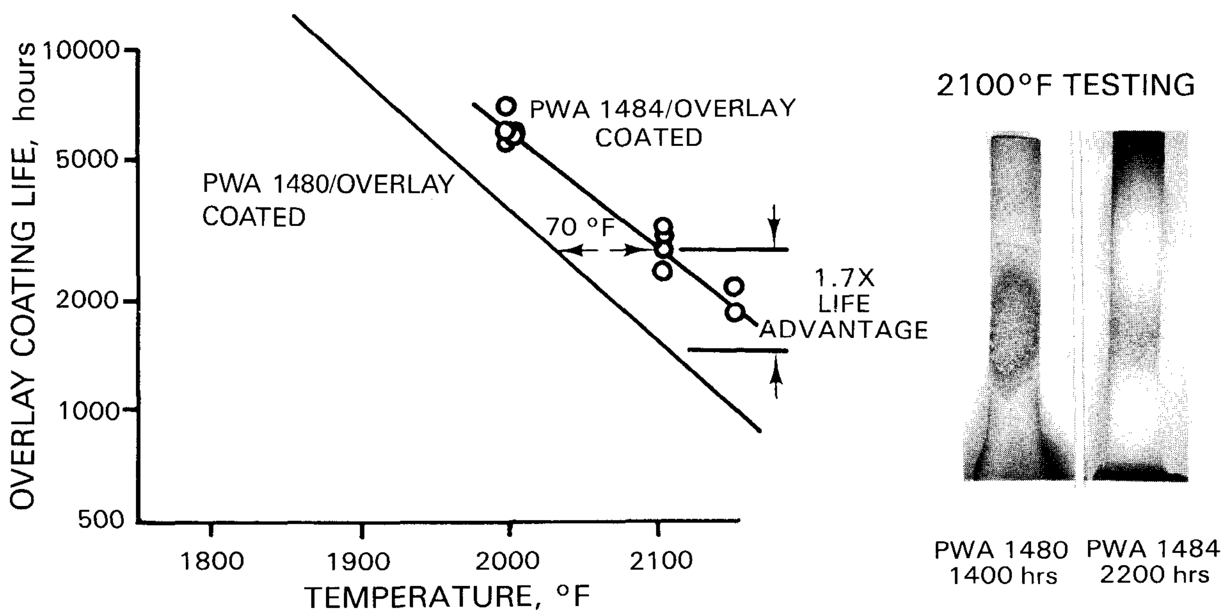


Figure 8 - Overlay coating exhibits significant increase in oxidation life on PWA 1484 compared to PWA 1480.

Thermal Fatigue Resistance

The thermal fatigue capability of the overlay NiCoCrAlHfSiY coated alloy was evaluated in a series of strain controlled thermal-mechanical fatigue (TMF) tests using hollow tube specimens. The strain and temperature components of the cycle employed were out-of-phase (maximum tensile strain at minimum temperature - Cycle I). Specimens were cycled between 800 and 1900°F and the tests were run until cracking was extensive, resulting in a 50% load drop. As shown in Figure 9, PWA 1484 specimens exhibited almost a 2X life advantage over PWA 1480 at a total strain range of 0.5%. This translates to a 65°F advantage in TMF temperature capability, which corresponds closely to the creep-rupture advantage exhibited by PWA 1484 over PWA 1480. Studies have indicated that elevated temperature TMF strength is related to alloy creep strength. It is believed that an alloy with increased creep strength is better able to resist the creep relaxation that occurs due to repeated cycling, which in turn increases the mean tensile stress imposed on the test specimen (9). The higher the mean tensile stress that develops, the lower the resulting TMF life.

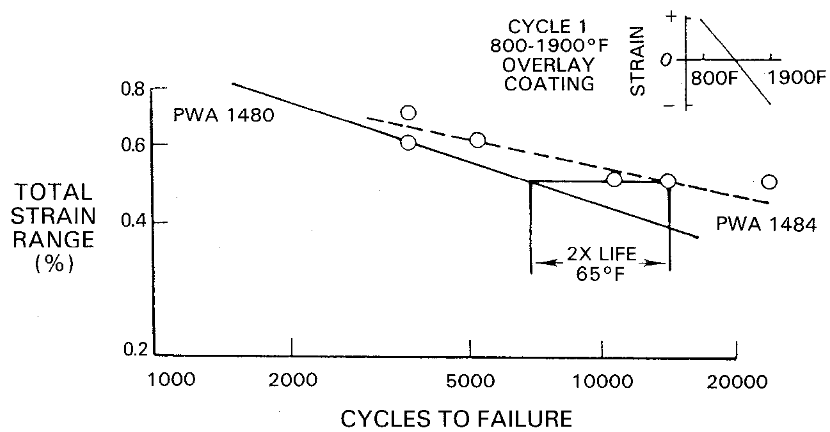


Figure 9 - PWA 1484 thermal fatigue life at 1900°F (T_{max}) is superior to PWA 1480.

High Cycle Fatigue

The fatigue capability of PWA 1484 has been extensively characterized in a series of smooth and notched axial high cycle fatigue (HCF) tests between 1100 and 1800°F. Modified Goodman diagrams for 10^7 cycle lives have been generated for the alloy in both the coated and uncoated conditions. PWA 1484 has excellent HCF capability especially in higher temperature (≥1600°F), higher mean stress (≥50 ksi) tests where its fatigue strength exceeds that of other alloys (Figure 10). The HCF conditions, in which sufficient time is spent at high stresses and temperatures to enable creep-fatigue interactions to occur, result in PWA 1484 displaying a significant advantage over other alloys due to its superior creep strength.

Castability

Casting trials have been conducted on PWA 1484 at both Pratt & Whitney and its casting supplier foundries, involving numerous blade and vane configurations (Figure 11), ranging from small (≤2 inch length) blades for helicopter engines to large (6 inch height x 3.5 inch chord) vanes for advanced military engines. Detailed inspections of the crystal quality and casting yields obtained in these trials demonstrated that PWA 1484 retains the excellent castability displayed by PWA 1480. Extensive experience gained by Pratt & Whitney's casting suppliers over the past four years in scaling up their casting processes, in preparation for production applications for PWA 1484, has confirmed the alloy's excellent castability. Post casting processing of PWA 1484 is similar to that for PWA 1480.

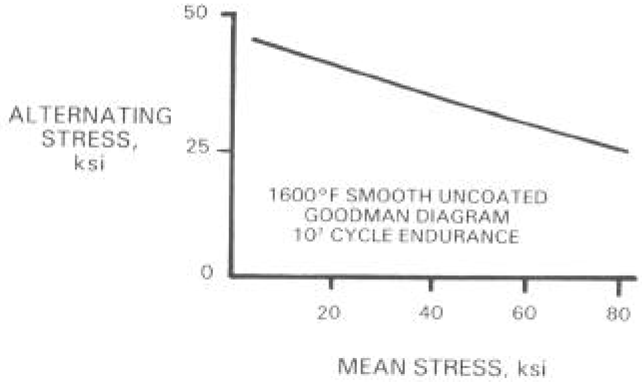


Figure 10 - High cycle fatigue strength of PWA 1484.

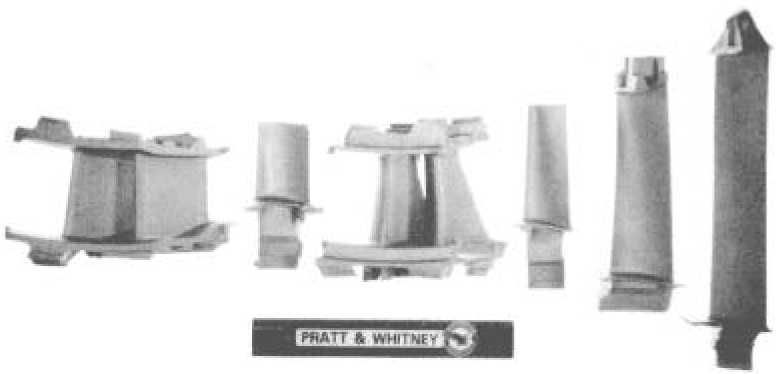


Figure 11 - PWA 1484 has been cast in a wide variety of airfoil configurations.

Engine Test Evaluation

Numerous engine tests of PWA 1484 turbine blades and vanes, in both military and commercial engines, has been successfully conducted over the last three years. This testing has confirmed the results of the laboratory characterization effort and demonstrated the excellent performance of PWA 1484. Growth measurements on PWA 1484 turbine blades have confirmed the low growth predicted by laboratory creep testing (Figure 12). Visual and metallographic evaluation of airfoils, engine tested for thousands of cycles under severe conditions, has shown them to be in excellent condition. Based on the successful engine test results, PWA 1484 will be employed as a turbine airfoil alloy in many advanced commercial and military engines. It is scheduled to enter production by the end of 1988.

Summary and Conclusions

A second-generation single crystal alloy, designated PWA 1484, has been identified which possesses more than a 50°F improvement in turbine airfoil capability compared to the strongest production single crystal alloys. The alloy displays good castability, has a large solution heat treatment range, and retains its microstructural stability after long-time thermal exposures. Extensive engine test evaluation of PWA 1484 has confirmed the excellent combination of properties displayed by the alloy in laboratory testing. The alloy is expected to enter production by the end of 1988.

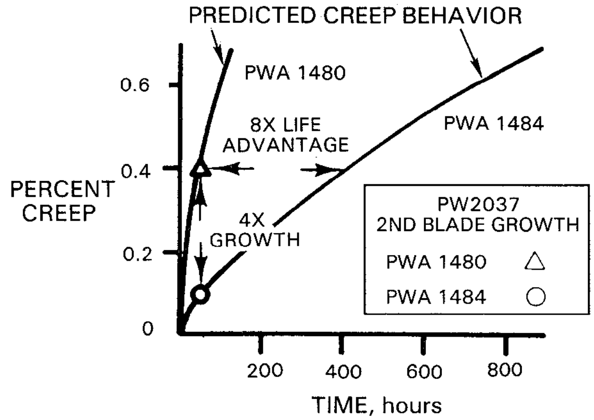


Figure 12 - PWA 1484 creep strength advantage confirmed in 2100 cycle PW2037 engine test.

Acknowledgement

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