SECOND GENERATION COLUMNAR GRAIN NICKEL-BASE SUPERALLOY

A. D. CETEL and D. N. DUHL

MATERIALS ENGINEERING
PRATT & WHITNEY
400 Main Street
East Hartford, Connecticut 06108

Abstract

High temperature strength capabilities similar to those of single crystal nickel-base alloys have been achieved in a second generation columnar grain alloy designed for advanced military and commercial turbine airfoil applications. This new alloy, designated PWA 1426, offers a 50F improvement in metal temperature capability (creep-rupture strength, thermal fatigue and oxidation resistance) over earlier columnar grain alloys (PWA 1422), and equivalent properties to current, production, first generation single crystal alloys, such as PWA 1480. In applications where PWA 1426 replaces PWA 1480, a major cost saving is realized due to the higher casting yields normally obtained with columnar grain castings relative to single crystals. Alloy properties have been fully characterized and demonstrate that PWA 1426 offers an outstanding combination of high temperature creep and fatigue strength, as well as excellent oxidation resistance and transverse ductility. Processing studies have shown it to have excellent castability and to be easy to solution heat treat in a production environment. The overall superior combination of properties, offered by PWA 1426, has been confirmed through an extensive series of engine tests leading to its incorporation in advanced military and commercial engines.

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Introduction

In an effort to meet the stringent turbine airfoil requirements for advanced commercial and military engines, while reducing turbine airfoil casting costs, an alloy development effort was initiated at Pratt & Whitney to define a second generation columnar grain alloy. Heretofore the major portion of the alloy development work in the industry over the last decade had been focused on single crystals, with only minor efforts devoted to columnar grain alloys. Interest in these alloys has been renewed by a desire to reduce manufacturing costs associated with casting single crystal turbine airfoils.

The demanding goals established for this program were to provide a columnar grain alloy that could replace PWA 1422, the first production columnar grain alloy, in advanced applications, as well as, cost effectively replace first generation single crystal alloys, such as PWA 1480. The alloy developed in this program was to offer the mechanical properties, oxidation resistance and microstructural stability of PWA 1480, while displaying the superior castability and ease of processing of PWA 1422.

Alloy Goals and Design Approach

The critical design goals established for the second generation columnar grain alloy were as follows:

1. Airfoil capability equivalent to PWA 1480
   a. Creep-rupture strength
   b. Coated and uncoated oxidation resistance
   c. Thermal fatigue resistance
2. Other critical properties
   a. Transverse ductility similar to PWA 1422
   b. Absence of secondary phase precipitation after long-time exposure
   c. High cycle fatigue strength comparable to PWA 1480
3. Reduced cost relative to PWA 1480
   a. Castability equivalent to PWA 1422
   b. Solution heat treatment range greater than PWA 1480

To meet these challenging goals, an extensive columnar grain alloy development effort was undertaken. This program took advantage of the knowledge gained in prior efforts at Pratt & Whitney over the last twenty years, including the single crystal work which led to the development of the second generation alloy PWA 1484 (Ref. 1).

Achieving strength levels in columnar grain alloys similar to those of single crystals had previously proven a difficult, if not unattainable goal, due to the natural limitations imposed on developers by polycrystalline alloys. A columnar grain alloy requires adequate grain boundary ductility to resist stresses transverse to the airfoil axis. This necessitates the inclusion of the grain boundary strengthening elements boron, carbon, zirconium and hafnium in the composition. Hafnium restricts the amount of refractory solid solution hardening elements that can be added to the alloy from a microstructural stability standpoint, while it and the other elements, except carbon, depress the alloy melting temperature. The gamma prime solvus temperature must be adjusted such that sufficient solutioning can be achieved during heat treatment to meet the creep strength goal without producing incipient melting.

To achieve an optimum combination of properties, a series of alloys were selected for the initial screening trials. From these alloys the minimum refractory element content required to meet the creep strength goal was established, as well as a definition of the critical microstructural stability-composition boundary limits. A minimum of 14-16 weight percent of the refractory elements (molybdenum, tungsten, tantalum and rhenium) was found to be necessary to achieve the strength goal. At refractory element contents beyond 16 weight percent, however, microstructural stability problems could be encountered. These studies also showed that a high volume fraction (60-65 volume percent) of gamma prime phase was required to meet the PWA 1480 strength goal.

The conflicting creep strength and microstructural stability goals require a delicate compositional balance. Additions of 3 weight percent rhenium were found to be necessary to successfully strike this balance. This element was determined to be an especially potent solid solution strengthener, as previously shown in the PWA 1484 single crystal program (Ref. 1). In the rhenium-free alloys of this study, the total refractory element content necessary to meet the creep strength goal had to be set so high as to preclude achieving a stable composition.

Achieving a high volume fraction of gamma prime phase in a high strength alloy, and still being able to attain adequate solutioning well below the incipient melting temperature, was another difficult task. Alloys containing 5.5 to 6.5 weight percent aluminum with low titanium and tantalum contents were selected for evaluation in this study. It was determined that an alloy with high temperature creep strength and a wide solution heat treatment processing window could be achieved in a titanium-free composition containing low to moderate levels of tantalum (3 to 5 weight percent). These screening trials indicated that an alloy capable of meeting all the program goals was attainable. The alloy which exhibited the best overall combination of properties was designated as PWA 1426. This second generation alloy is compared to a first generation columnar grain alloy (PWA 1422) and first and second generation single crystal alloys (PWA 1480 and PWA 1484, respectively) in Table I.

Table I

Composition (weight percent)

Alloy	Ni	Cr	Ti	Mo	W	Re	Ta	Al	Co	B	Zr	C	Hf
PWA 1422	Bal.	9	2	-	12	-	(1Cb)	5	10	.015	.1	.14	1.5
PWA 1480	Bal.	10	1.5	-	4	-	12	5	5	—	-	—	—
PWA 1484	Bal.	5	-	2	6	3	8.7	5.6	10	—	-	—	.1
PWA 1426	Bal.	6.5	-	1.7	6.5	3	4	6	10	.015	.1	.1	1.5

PWA 1426 Heat Treatment: 2240F/4hrs.+ 1975F/4hrs.+ 1600F/12hrs.

Alloy Microstructure and Properties

Effect of Solution Heat Treatment on Microstructure and Properties

To provide for some degree of flexibility in meeting two major program goals, ease of processing and transverse ductility, the alloy composition was designed such that the PWA 1480 creep strength goal could be met by only partial solutioning of the gamma prime phase. As shown in Figure 1, the 1800F creep strength of PWA 1426 is directly related to the volume fraction of gamma prime phase solutioned and reprecipitated as fine particles during heat treatment. With nearly full solutioning (2275F heat treatment) rupture lives were observed to be more than double the program goal, while with only minimal solutioning (2200F heat treatment) the goal still could be achieved. This provided the alloy with a large (>50F) temperature range over which the alloy could be heat treated, and one that was well below its incipient melting temperature (2300F). The need for only partial solutioning of its gamma prime phase had an additional benefit on the transverse ductility of the alloy. As shown in Figure 2, transverse creep ductility is inversely related to the extent of gamma prime solutioning, especially at 1400F. If the amount of solutioning necessary to meet the PWA 1480 level of creep strength can be minimized, then both the heat treatment window for the alloy, as well as its transverse ductility, can be improved. A nominal 2240F solution heat treatment cycle was selected for PWA 1426, which enables the creep-rupture strength goal to be met, and provides a practical processing range of greater than 50F.

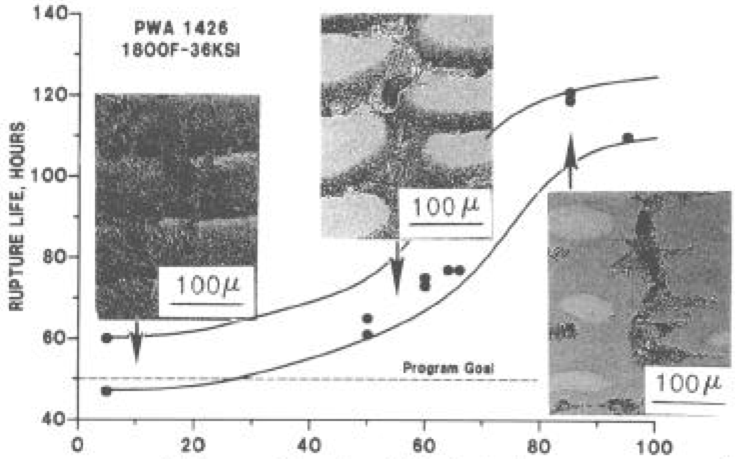


Figure 1 - PWA 1426 Creep-Rupture Strength Goal Can Be Met at Low Levels of Gamma Prime Solutioning

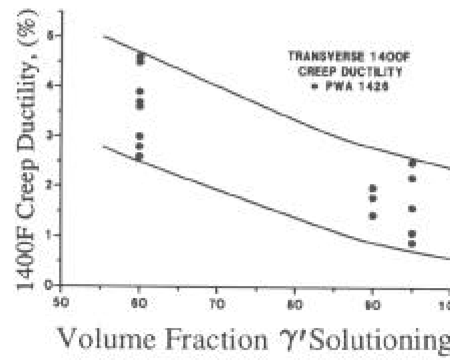


Figure 2 - Transverse Creep Ductility is Very Sensitive to the Volume Fraction of Gamma Prime Taken into Solution

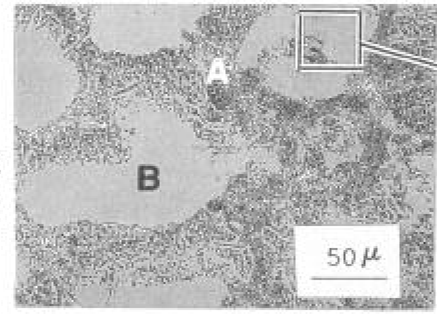
The full heat treatment for PWA 1426, as shown in Table 1, consists of a three step process. A 2240F for 4 hour solution heat treatment with a rapid cooling cycle was selected to achieve approximately 50% gamma prime solutioning and a fine size distribution (<.4 microns) for those particles taken into solution and reprecipitated (Figure 3). This is followed by a 1975F for 4 hour coating cycle to bond the coating to the alloy, as well as to produce an optimum gamma prime particle size and uniform distribution. To enhance intermediate temperature yield strength, the alloy heat treatment utilizes a 1600F for 12 hour aging cycle. After full heat treatment, a fine gamma prime size is retained in the solutioned and reprecipitated particles (Figure 3) due to the rapid cooling cycle employed and the retardation of coarsening resulting from the rhenium contained in the composition.

Effect of Cooling Rate and Exposure on Microstructure and Properties

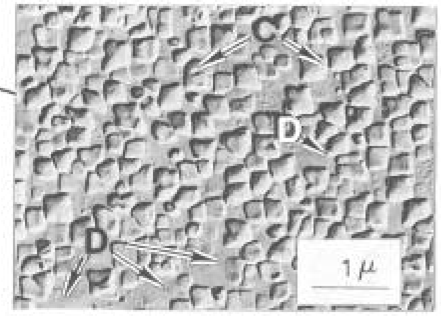
The effect of variation in the cooling rate employed in the solution heat treatment cycle was studied as a means to optimize alloy creep and tensile properties. It is well known (Ref. 2) that cooling rates have a strong influence on nickel-base superalloy properties by their effect on gamma prime particle sizes. The faster the cooling rate, the finer the particle size that reprecipitates from the solution temperature. Particle sizes ranging from .23 μ at 300F/minute to .47 μ at 44F/minute were evaluated in this study.

Creep-rupture testing at 1400,1600 and 1800F, and 1100F tensile testing was employed to evaluate the effect of cooling rate on mechanical properties. This study confirmed that cooling rates could strongly influence certain alloy properties, such as intermediate temperature creep-rupture strength. Cooling rate and gamma prime size were found to have only a small effect on 1100F tensile strength. Creep-rupture lives on the other hand improved between 30 and 100% (at 1800 and 1400F, respectively) when cooling rates were increased from 40 to 125F per minute

As solutioned
2240F (4 hrs)

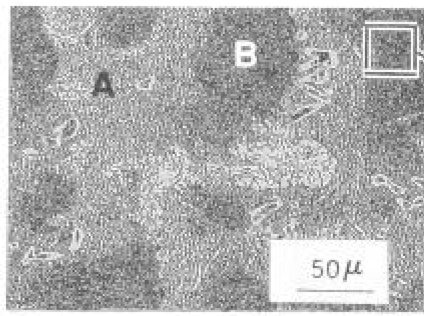


Coarse gamma prime particles (A) and unresolved gamma prime precipitates in gamma matrix (B)

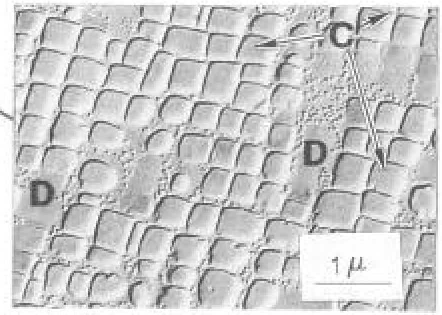


Fine uniform array of gamma prime particles (C) in gamma matrix (D)

Fully heat treated
2240F (4 hrs)+
1975F (4 hrs)+
1600F (12 hrs)



Coarse gamma prime particles (A) and partially resolved gamma prime precipitates in gamma matrix (B)



Fine uniform array of gamma prime particles (C) in gamma matrix (D)

Figure 3 - Typical Microstructure of Solution Heat Treated (TOP) and Fully Heat Treated PWA1426 (BOTTOM) Showing Fine Gamma Prime Particle Size Retained in Dendrite Cores

(Figure 4). Beyond the 125F per minute rate, little further change in rupture life was observed, although lives appeared to start declining slightly at very rapid rates (producing fine gamma prime sizes), especially at 1400F. Rupture life was shown to be sensitive to particle size at 1400F, with life optimized within a range of sizes between .25 and .45 microns, while at 1800F less sensitivity to size was observed as shown in Figure 5.

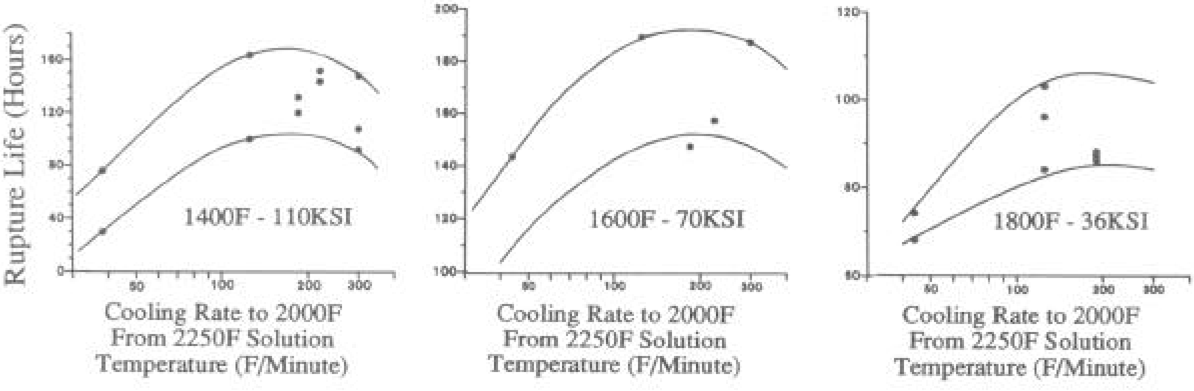


Figure 4 - PWA1426 Creep-Rupture Strength is Optimized by Employing Cooling Rates from the Solution Heat Treatment Temperature Greater than 100F per minute

A study was conducted to compare the coarsening rates of gamma prime particles in PWA 1426 and PWA 1480 at 1975 and 2000F, to gain a better understanding of the high temperature strength capabilities of the alloys. It also provided an early assessment of each alloy's relative sensitivity to the high temperature exposures that would be encountered during coating refurbishment and service operation. The gamma prime coarsening rates for both alloys were observed to be almost identical (Figure 6). This gave a good indication that the high temperature capabilities of PWA 1426 and PWA 1480 would prove to be comparable.

The PWA 1426 composition was designed to be free of secondary phase instabilities after long-time elevated temperature exposures. Metallographic evaluation of specimens furnace exposed for 1000 hours, as well as specimens creep tested for up to 2000 hours between 1600 and 2000F has confirmed the excellent microstructural stability of the alloy.

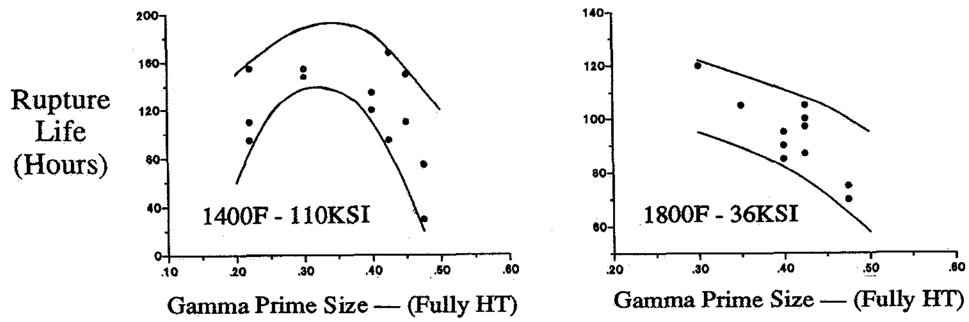


Figure 5 - Effect of Gamma Prime Size on the Creep-Rupture Strength of PWA 1426. Note that Strength is Optimized at Sizes Between 0.25 and 0.45μ at 1400F (LEFT) While at 1800F (RIGHT) There is Less Sensitivity to Size

Alloy Property Characterization

Creep-Rupture Strength

An extensive characterization (involving more than 100 tests) of the creep-rupture strength of PWA 1426 was conducted between 1400 and 2100F, employing specimens machined from both cast bars and blades. The alloy was determined to meet or exceed the PWA 1480 creep strength goal between 1500 and 2000F, as shown in a comparison of stress rupture capability (stress for rupture in 300 hours) plotted versus temperature in Figure 7. Long-time creep-rupture data from several large commercial heats are compared with data obtained in shorter time (<500 hour) tests, in Figure 8. This Larson-Miller comparison shows that both sets of data can be represented by one curve and are thus equivalent. This demonstrates that PWA 1426 maintains its creep capability in long-time tests and that creep lives for the alloy can be successfully projected out to more than 2000 hours from shorter time data.

Tensile and Impact Properties

The tensile properties of PWA 1426 have been characterized in a series of tests between room temperature and 2100F Figure 9. The yield strength of the alloy is similar to that of PWA 1480 at low temperatures (<1200F) and superior at higher temperatures (1500 to 2000F). Despite its outstanding yield strength, the alloy displays excellent tensile ductility at all temperatures evaluated, with typical elongations exceeding 10%.

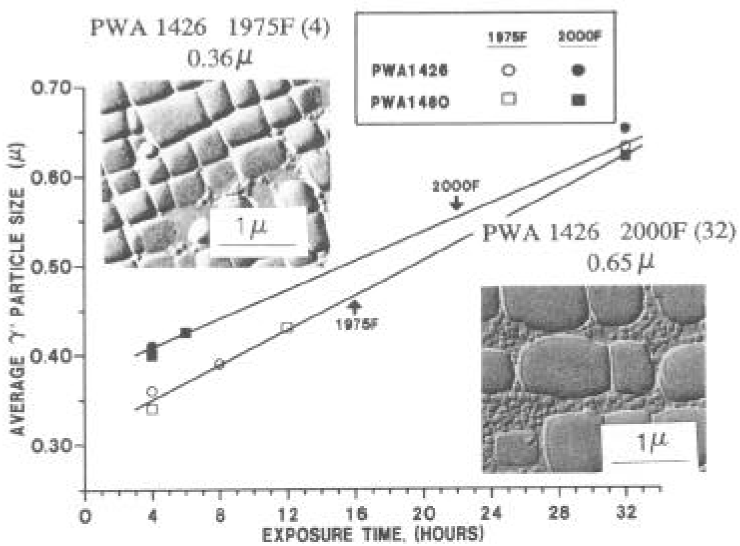


Figure 6 - Gamma Prime Particle Coarsening Rates for PWA 1426 and PWA 1480 are equivalent between 1975F and 2000F

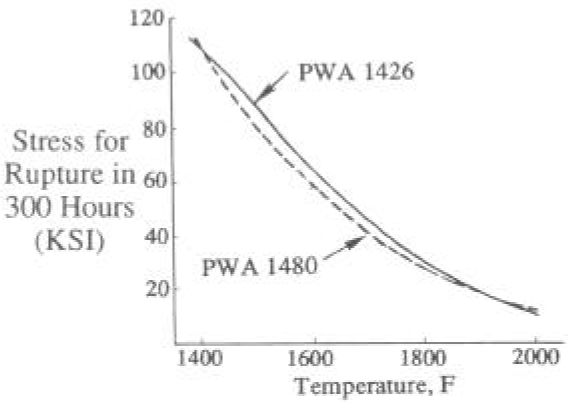


Figure 7 - PWA 1426 Creep-Rupture Capability Shown to Meet or Exceed PWA 1480 Strength Levels

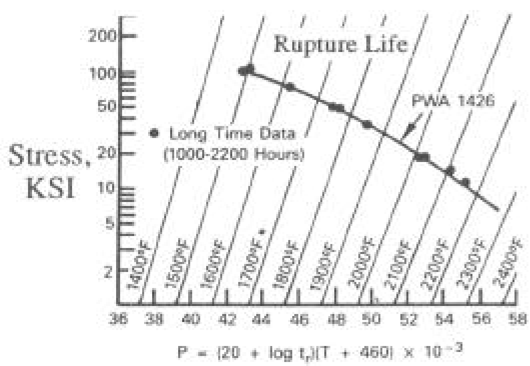


Figure 8 - Long Time PWA 1426 Creep-Rupture Data Lies on Curve Based on Short-Time Data

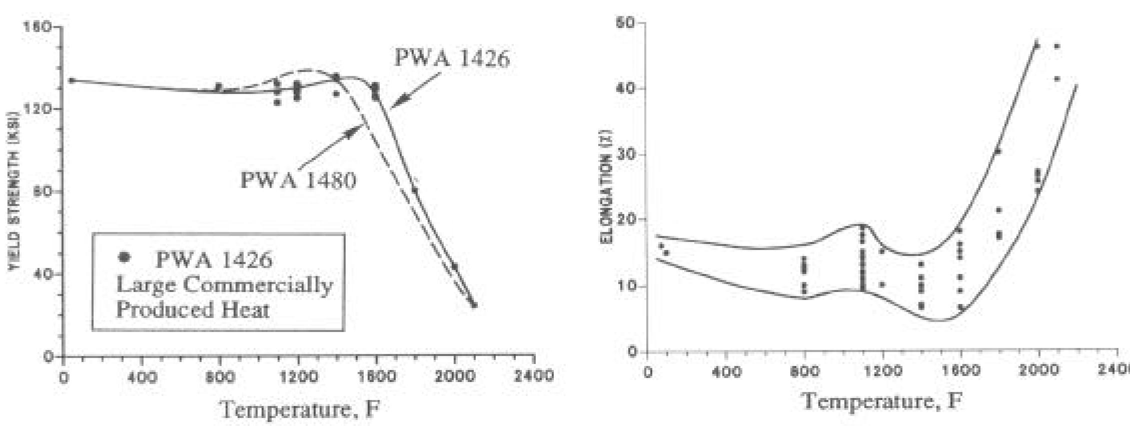


Figure 9 - PWA1426 Exhibits Yield Strength Meeting or Exceeding the PWA1480 Goal (TOP) and Excellent Ductility at all Temperatures (BOTTOM)

The ability to resist foreign object damage is an important design consideration for turbine airfoil materials. This capability was evaluated in Charpy impact tests conducted on specimens between 1600 and 2000F. PWA 1426 displayed excellent impact resistance (greater than 50 foot-pounds) over this entire range of temperatures, and greater resistance than either PWA 1422 or PWA 1480. This outstanding capability is derived from the alloy's excellent combination of high yield strength and ductility.

Oxidation and Hot Corrosion Resistance

The PWA 1426 alloy composition was designed from its inception to have a high level of oxidation resistance, comparable to PWA 1480. This would enable it to replace columnar grain and single crystal alloys in many high temperature applications where oxidation resistance is critical. Burner rig testing was conducted on both coated and uncoated erosion bar specimens at 2100F, which confirmed that the program oxidation goals had been attained. Uncoated specimens were shown to oxidize at rates comparable to PWA 1480 (Figure 10). Tests conducted with a NiCoCrAlSiY overlay coating indicated that this coating had a slightly lower life when applied to the PWA 1426 substrate than to PWA 1480. This reduced life was not judged to be a serious limitation, and may be attributable to the diffusion of the minor elements, present in the PWA 1426 composition, into the coating. With an aluminide coating, PWA 1426 displays improved oxidation life, compared with PWA 1480. This may be a result of the diffusion of hafnium from the substrate, into the coating, promoting alumina scale adherence. The overall excellent oxidation resistance of PWA 1426 is attributable to its high aluminum content (6%), which promotes oxidation resistance, and minimization of elements such as titanium (eliminated) and tungsten (6.5%) which reduce life.

The hot corrosion resistance of PWA 1426 was evaluated under severe conditions in a series of ducted burner rig tests at 1650F. Aggressive corrosion conditions were produced by injecting a highly concentrated synthetic sea salt solution into the combustion flame before it impinged on the test specimens. These tests demonstrated that PWA 1426 retained a high level of hot corrosion resistance, similar to PWA 1480 and other high strength turbine airfoil alloys.

Thermal Fatigue and High Cycle 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 employing hollow tube specimens. The strain and temperature components of this cycle were out of phase (maximum tensile strain at minimum temperature - Cycle I). Specimens were cycled between 800 and 1900F and the tests were run until cracking was extensive, resulting in a 50% load drop. As shown in Figure 11, PWA 1426 specimens exhibited lives comparable to those of PWA 1480 which is related to their similar creep strengths. It is believed that creep strength influences the amount of creep relaxation produced by TMF cycling, which in turn influences the mean stress imposed on the test specimen, controlling life (Ref. 3).

The high cycle fatigue (HCF) capability of PWA 1426 has been characterized in a series of smooth and notched axial high cycle fatigue (HCF) tests at 1400 and 1600F. Modified Goodman diagrams for 10^7 cycle lives, generated for the alloy, demonstrated that PWA 1426 has excellent HCF capability. This is especially true at higher temperature ($\geq$1600F) and higher mean stress (>50ksi) conditions, where its fatigue strength slightly exceeds that of PWA 1480. Those HCF conditions in which sufficient time is spent at high stresses and temperatures to enable creep-fatigue interactions to occur, result in PWA 1426 displaying a small advantage (at 1600F) over PWA 1480 due to its superior creep strength.

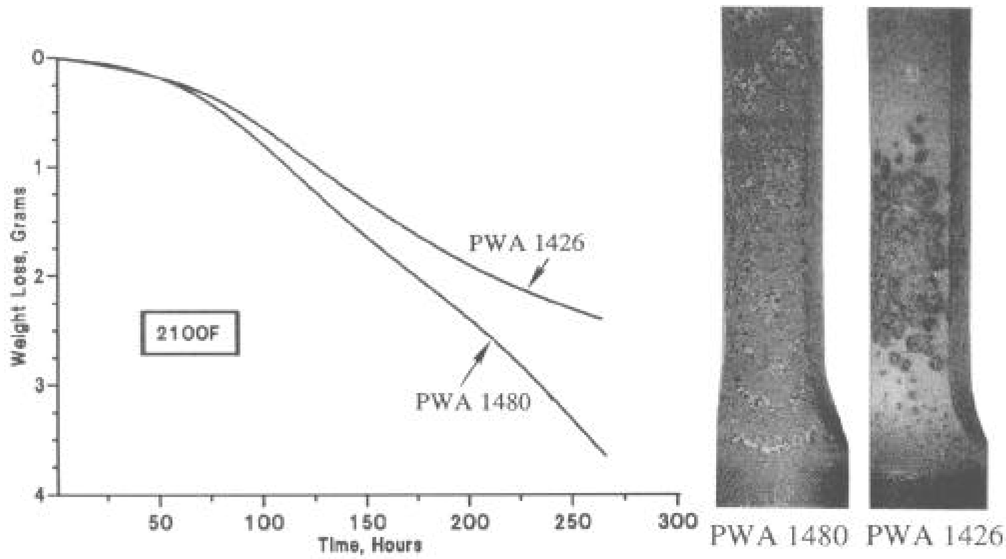


Figure 10 - Uncoated Burner Rig Oxidation Resistance of PWA1426 and PWA1480 are similar at 2100F

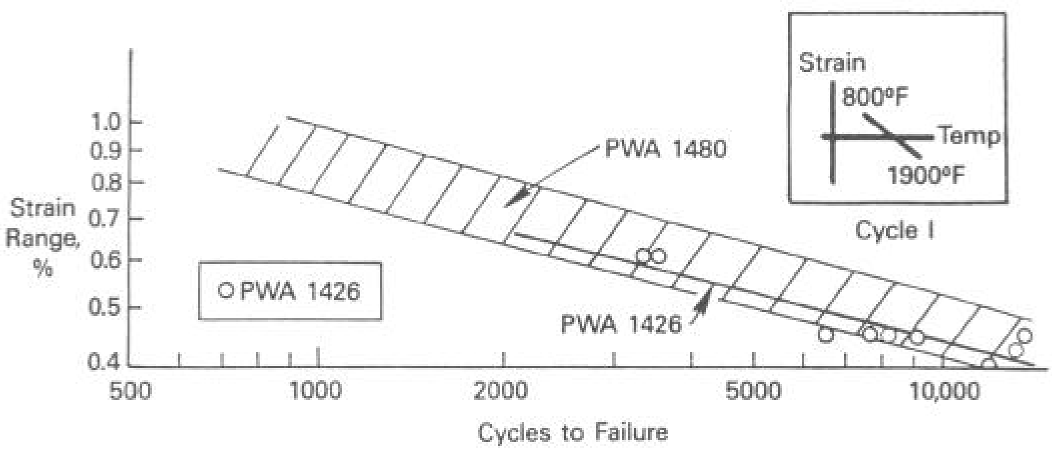


Figure 11 - PWA1426 Exhibits Thermal Fatigue Resistance Similar to PWA1480

Castability

Early in the development of PWA 1426, alloy casting trials were conducted at both Pratt & Whitney and its casting supplier foundries to gain an initial assessment of the alloy's castability. Numerous blade and vane configurations were cast, ranging from small (<2 inch length) blades to large (6 inch height by 4 inch chord) vanes. Detailed inspection of the quality and casting yields obtained in these trials, demonstrated that PWA 1426 retains the excellent castability displayed by PWA 1422, which was one of the prime objectives of this program.

Extensive experience has been gained by Pratt & Whitney's casting suppliers over the past three years in producing production quantities of PWA 1426 castings. This has confirmed the alloy's excellent castability and that castings can be procured at a considerable cost saving compared to PWA 1480.

Engine Testing

Prior to releasing the alloy for production engine applications, an extensive experimental engine test program was conducted under very severe operating conditions. The alloy was evaluated in both turbine blade and vane applications in military and commercial engines, over the last five years. Growth measurements obtained on mixed alloy rotors of turbine blades after engine test, confirmed that the PWA1426 blades behaved similarly to PWA 1480, as predicted by laboratory creep testing. Visual and metallographic evaluation of airfoils after thousands of cycles of severe operation has shown them to be in excellent condition, from both an oxidation and a cracking standpoint. From the successful completion of this engine test program it was concluded that the alloy performed similarly to PWA 1480, as had been previously shown in the laboratory characterization effort. PWA 1426 turbine components entered production in several advanced military (F100-PW-229) and commercial (PW2037) applications in 1990.

Summary and Conclusions

A second generation columnar grain alloy, designated PWA 1426, has been identified, which possesses turbine airfoil properties comparable to PWA 1480, the first production single crystal alloy. The alloy has been extensively evaluated in both laboratory and experimental engine test programs. The attractive combination of high temperature strength, oxidation resistance and castability offered by this alloy make it an ideal candidate to replace PWA 1480 in many applications and in so doing realize a significant cost saving. The alloy has recently entered production in several advanced military and commercial applications.

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