A New Development in Gas Turbine Materials: The Properties and Characteristics of PWA 664

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A review of high-temperature gas-turbine materials shows that improvements in creep resistance are often achieved at the expense of other desirable properties, such as ductility and resistance to thermal shock and to oxidation. A precision casting technique based on directional solidification, which imparts ductility and thermal shock resistance to high-temperature creep-resistant superalloys, has been developed at Pratt & Whitney Aircraft. The desired improvement in physical properties is achieved by controlling solidification so as to eliminate grain boundaries transverse to the major stress axis of a component. Gas-turbine blades and vanes have been cast to size in various complex shapes. Components and test-bars were fabricated from the same nickel-base superalloy, Mar-M200, following either "conventional casting" or "directional solidification" techniques. The materials resulting from the two processes are designated PWA 659 and PWA 664, respectively. Laboratory tests show that PWA 664 is superior to PWA 659, both in strength and ductility. Uncoated PWA 664 turbine blades outlasted coated PWA 659 blades when tested in an engine. PWA 664 demonstrates greater resistance to deformation at 2000°F, and superior thermal shock resistance as compared to the current vane material (W152 cobalt-base alloy). When tested as a vane, PWA 664 was found to be more durable and bow-resistant than W152.

Gas-Turbine Blades

Introduction

THE development of the gas-turbine engine has been hampered since its conception by the availability of materials that will withstand high stress at elevated temperature. This need has been fulfilled by the development of a series of nickel-base and cobalt-base alloys that satisfied the unique requirements of turbine blades and vanes, respectively. During the past decade the stringent requirements of a first-stage turbine blade were met by the use of forged nickel-base superalloys as opposed to precision castings. The systematic development of the wrought superalloy was delayed and at times halted, however, when it was discovered that the increases in strength obtained by compositional variation were only achieved with a loss in workability and ductility. For example, the exploitation of Nimonic 95,[1]‡ a modification of Nimonic 90 having increased titanium and aluminum levels, was accomplished only by the development of improved methods of hot working.

Since it was recognized that high-temperature strength was incompatible with workability, it appeared that further development of alloys for gas-turbine blades could only occur with the use of cast alloys, particularly as the more advanced forgeable alloys were found to possess superior creep strength in the as-cast condition. The use of castings allowed even larger additions of strengthening elements to be made, and several alloys were developed having strengths suitable for further increases in service temperature. Alloys typical of this group include PWA 658 [IN-100[2]] and PWA 659 [Mar-M200[3]] which contain 5.5% Al, 5% Ti, and 3% Mo and 5.0% Al, 2% Ti, and 12% W, respectively. In order to make these additions, however, the chromium contents of the two alloys were adjusted to 10 and 9%, respectively. In consequence, the increase in strength was made only at the expense of oxidation resistance. The solution of this dilemma appeared to present almost insurmountable difficulties, and present day development of nickel-base alloys is mainly confined to a search for a balanced combination of properties for gas-turbine blading.

Investigation of sound cast material free from microporosity and inclusions has shown that the high-strength, cast nickel-base alloy has less ductility than is desirable, as evidenced by its low tensile and stress-rupture ductilities, particularly in the intermediate temperature range. Furthermore, almost all high-strength nickel-base alloys are found to be susceptible to thermal shock. The common mode of failure of the cast super-alloy during testing is intergranular, usually along grain-boundaries normal to the direction of applied stress. In creep testing the rapid propagation of intercrystalline cracks results in premature failure and the absence of third-stage creep may be noticed. If microporosity is present in the highly stressed root section of cast turbine blades, this general lack of ductility is accentuated.

It became apparent that a new approach was required which would allow the development of alloys with increased strength for use at higher service temperatures without sacrificing other desirable properties such as ductility and thermal shock resistance. Based on previous work,[4] the solution to the lack of ductility of nickel-base superalloys appeared to be the elimination of the source of failure, namely the presence of grain-boundaries normal to the direction of applied stress. In accordance with this line of reasoning a method of casting nickel-base superalloys has been developed at the Advanced Materials Research and Development Laboratory, which produces longitudinal columnar grains in complex-shaped gas-turbine hardware such that they contain no transverse grain-boundaries. Either vanes or blades may be cast with cast-to-size airfoil sections ready for conventional machining. The material resulting from the application of this process to the alloy Mar-M200 is known as PWA 664. One effect of the

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‡ The compositions of alloys referred to are reported in Table 1.

Table 1 Nominal compositions of nickel and cobalt-base alloys

PWA no.	Common designation	C	Cr	W	Mo	Ta + Cb	Al	Ti	Co	Ni
...	Nimonic 90	0.1	20	...	...	...	1.4	2.4	18	Bal.
...	Nimonic 95	0.1	20	...	...	...	2.0	2.9	18	Bal.
658	IN 100	0.18	10	...	3	...	5.5	5	15	Bal.
659	Mar-M200	0.15	9	12.0	...	1	5	2	10	Bal.
664	D.S. 200	0.13	9	12.0	...	1	5	2	10	Bal.
AMS 5385	Vitallium	0.25	27	...	5.5	...	...	...	Bal.	2.75
653	WI-52	0.45	21	11	...	2	...	...	Bal.	...
657	Mar-M302	0.85	21.5	10	...	9	...	...	Bal.	...

process is shown in Fig. 1, where a PWA 664 turbine blade casting is shown after being subjected to a cold transverse bend test. The process results in the grains being preferentially oriented in a [100] direction; that is, the cube axis of the unit cells are aligned parallel to the axis of the airfoil. Because of this, the modulus of elasticity of the material measured in a direction parallel with the axis of the columnar grains is approximately $\frac{2}{3}$ that of the conventionally cast alloy. The modulus of elasticity of the material transverse to the long axis of the columnar grains is approximately $\frac{5}{6}$ that of the conventionally cast alloy; that is, an average of $E_{<100>}$ and $E_{<110>}$. (Note: the elastic constants for pure nickel single crystals are $E_{<100>} = 18.2 \times 10^6$ psi, $E_{<110>} = 31.9 \times 10^6$ psi, and $E_{<111>} = 42.6 \times 10^6$ psi.)

PWA 664 Blade Processing

During the initial testing of PWA 664 it soon became clear that the process had imparted both ductility and longer life to Mar-M200. Since the conventionally cast alloy had already been qualified by engine test, it was decided at the onset that an engine test would provide the most useful and demonstrative comparison of the two materials. The technique was applied to the fabrication of JT4 turbine blades by redesigning conventional investment shell molds. The blades were cast in groups of five and the blade mold cavity designed such that the cross section of the cavity decreased in size with distance from the bottom. In molds designed for conventional casting, the mold is usually arranged so that the thicker sections are close to the feeder head, that is, at the top of the casting. The growth of columnar grains with a preferred orientation requires both a steep temperature gradient, such as may be imposed by replacing the ceramic mold bottom with a water-cooled copper chill, and that the grains be unrestricted in their growth; otherwise a misoriented grain structure will result. Since only true directional solidification occurs, that is, a progressive movement of the solid-liquid interface, sound castings resulted with a marked absence of microporosity common to conventionally cast thick sections. The resultant process was put into development with castings made at the Advanced Materials Research and Development Laboratory and the Experimental Foundry, Manchester. Ultimately parts were produced in sizeable numbers at the Metals Division of TRW Inc.

After separating each blade from a five-blade casting and rejecting any with obvious casting defects, they were each sand blasted and etched to reveal the microstructure. Blades with an acceptable grain structure were defined as consisting totally of columnar grains with little divergence of the grain orientation or variation in grain size. A blade may be "side-nucleated"; that is, although the blade appears totally columnar, close examination shows that grains have been nucleated at the mold face in the vicinity of the blade platform, the resultant grains varying in both orientation and size. It has been shown that such grains, although columnar, do not have the required preferred crystallographic orientation and have poorer mechanical properties.

The excess material from both the top and bottom of each blade was then removed and used for chemical and metallographic analysis. Any blade whose composition was not within specification was rejected. The blades were then machined. Finally, visual x-ray and zyglo inspection was carried out before delivery of the blades for measurement of size and engine test. The initial program resulted in 47 acceptable PWA 664 turbine blades.

Engine Testing of Blades

When PWA 659 was initially engine tested as a first-stage blade, it was discovered that the uncoated material could withstand only about 200 endurance cycles (approximately 17 hr) before intergranular cracking was noticed. When the material was used in conjunction with the PWA-47-14L coating,§ 50 hr elapsed before cracking was observed, an increase in life of 300%. It has been established that coated PWA 659 is the most creep resistant of the nickel-base superalloys, and it was considered that it would serve as a good comparison for any material developed subsequently. Because of the directional nature of the grain-boundaries in PWA 664, however, it appeared possible that the premature grain-boundary failure common to conventionally cast superalloys would not occur. The decision was made, therefore, to compared uncoated PWA 664 with coated PWA 659. Typical blades are shown in the macroteched condition in Fig. 2.

The 47 PWA 664 turbine blades, together with 49 PWA 659 turbine blades coated with PWA-47-14L, were assembled (in

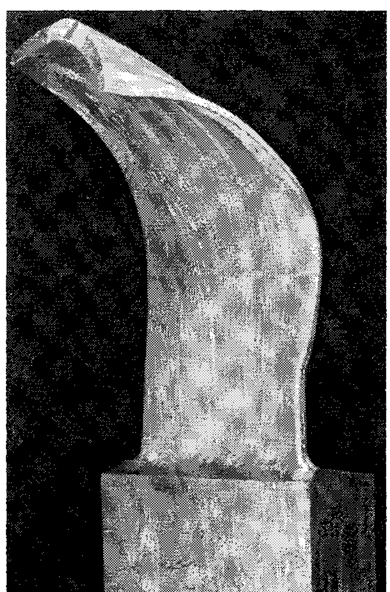


Fig. 1 PWA 664 JT4 turbine blade casting after transverse bend testing at room temperature (70°F).

§ A sprayed aluminum-silicon slurry followed by a 2000°F diffusion heat treatment.

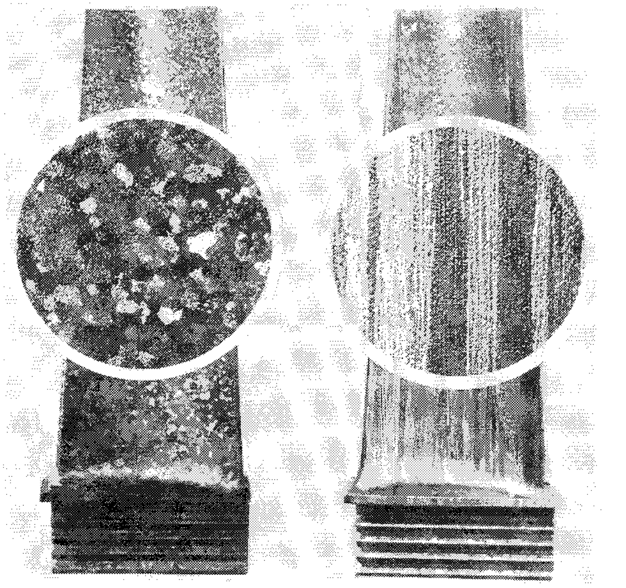


Fig. 2 Conventionally cast PWA 659, shroudless JT4 test blade in macroetched condition showing normal grain structure and directionally solidified PWA 664, shroudless JT4 test blade in macroetched condition showing columnar grain structure.

alternate positions) in the first-stage turbine rotor of a JT4 experimental engine. The engine was calibrated and an approximate turbine inlet temperature set at 1920°F. The intention of the test was to run 15 endurance cycles before a hot section inspection. Each endurance cycle consisted of six 5-min periods at maximum inlet temperature alternated with 2-min idle periods followed by five 30-sec periods at maximum inlet temperature alternated with 2-min idle periods followed by 30 min at maximum inlet temperature steady state. This is approximately 1 hr total hot time and 12 thermal cycles per endurance cycle. Because of the failure of a fuel manifold, the test was interrupted at 11 hr of endurance, at which time the turbine blades were removed and measured. One of the PWA 664 turbine blades was removed for laboratory evaluation and was replaced with a PWA 659 blade, making a total of 50 PWA 659 blades and 46 PWA 664 blades. The engine was subsequently operated for 20 hr at a turbine inlet temperature of 1865°F, 10.9 hr at 1920°F, 8.1 hr at 1965°F, 15.5 hr at 2020°F, and a further 4.5 hr at 2020°F. The blade growth was measured at the end of each of these intervals, i.e., after 11, 31, 50, 65.5, and 70 hr.

The blades were examined after 65.5 hr and the following observations were made:

1) Several of the coated PWA 659 blades contained cracks at the leading and/or trailing edges, but very little oxidation was apparent.

2) The uncoated PWA 664 blades, although showing substantial oxidation, contained no leading or trailing edge cracks. One of the PWA 664 blades had a longitudinal groove in a midspan midchord position.

At the end of 65.5 hr, 10 of the coated PWA 659 blades were replaced with 10 uncoated PWA 659 blades in order to confirm the value of the coating to PWA 659. After another 4.5 hr of engine test at 2020°F, the blades were again removed from the rotor, measured and examined. The observations were as follows:

1) Twenty of the forty coated PWA 659 blades contained leading edge indications and cracks, one of which was $\frac{1}{4}$ in. in length. This blade is shown in Fig. 3 compared with a typical PWA 664 blade.

2) Two of the 46 PWA 664 blades contained leading edge indications of less than $\frac{1}{16}$ in. in length. The larger of these two indications, however, was observed at 50 hr and did not appear to have propagated significantly compared to the rapid initiation and propagation of the cracks in the PWA 659 blades. Zyglo examination also showed that the indications in the two PWA 664 blades were less sharp than those in the PWA 659 and were better described as "grooves" rather than cracks. Several of the PWA 664 blades contained longitudinal grooves of the type observed at 65.5 hr.

3) Three of the ten uncoated PWA 659 blades contained zyglo indications.

4) All the blades were visibly distorted in the hot zone, but the distortion was somewhat more pronounced in the PWA 659.

The presence of cracks in 50% of the PWA 659 turbine blades indicates that the true life of this material under these conditions had been determined. On the other hand, the PWA 664 blades were still considered serviceable and available for continued engine testing. The successful completion of 70.0 hr of endurance, i.e., approximately 816 cycles by the two materials, supports earlier reports that the application of the PWA-47-14L coating to PWA 659 improves its life by more than a factor of 3. Furthermore, it shows that in the absence of transverse grain-boundaries the life of Mar-M200 is substantially increased. This information confirms the assumption that grain-boundaries perpendicular to the axis of the turbine blade serve as a source of failure. It may thus be concluded that the grain-boundaries are weaker and are less resistant to oxidation than the bulk material. The oxidation resistance of the alloy is unaffected by grain structure, however, and remains poor at high temperatures as the condition of the uncoated PWA 664 blades shows. The longitudinal grooving observed is undoubtedly the result of preferential grain-boundary oxidation. Such oxidation has been shown to deplete the surface of the alloy in aluminum and titanium, on which the strength of the alloy relies. It would be expected, therefore, that PWA 664 turbine glades would weaken with time in the uncoated condition.

The results of growth measurement (maximum, minimum, and average) of the PWA 664 and PWA 659 turbine blades are presented graphically in Fig. 4. They show that PWA 664 blades gave more consistent results, there being less spread between maximum and minimum, and that during the first 50 hr of test PWA 664 shows, on the average, less growth than the coated PWA 659. The exposure at 2020°F for 20.0 hr resulted, however, in a convergence of the growth measurements of the two materials. The fact that uncoated PWA 664 survived over three times the life of uncoated PWA 659 and still

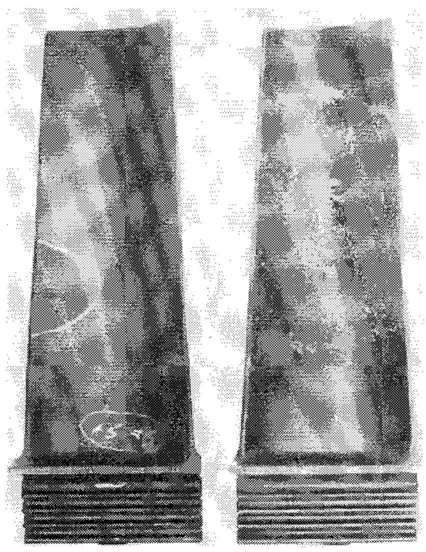


Fig. 3 PWA 659 (coated) and PWA 664 (uncoated) turbine blades after 70.0 hr of engine test. Note the transverse crack in the leading edge of the PWA 659 blade. Severe oxidation of the PWA 664 blade is caused by the absence of a coating.

showed no indication of serious cracking demonstrated that the process represents a real advance in the development of gas turbine hardware.

Gas-Turbine Vanes

Introduction

The requirements of a gas-turbine vane are bow resistance, oxidation resistance, and thermal shock resistance. These requirements have been met, until recently, by relatively few cast cobalt-base alloys. In fact only three alloys, AMS 5385 (vitallium), PWA 653 (WI-52), and PWA 657 (Mar-M302) have been used extensively in Pratt & Whitney Aircraft engines.

Experience has shown that an increase in turbine inlet temperature will require a vane material with greater bow resistance than these alloys. The increase in bow resistance also must be developed without a loss in resistance to thermal shock.

Laboratory and rig testing during the early stages of this program indicated that the thermal shock resistance of PWA 664 was superior to most cast nickel-base alloys. Furthermore, in view of the high creep resistance of the material compared with WI-52 and Mar-M302, it was believed that the material might perform well as a vane. The following account describes the steps taken in its evaluation as a gas-turbine vane.

PWA 664 Vane Processing

Gas-turbine vanes were made in a manner similar to the blades with the exception that cores were necessarily incorporated into the mold to produce hollow parts. A method was developed of pinning the ceramic core so that the open-end mold technique could be used to provide controlled columnar grains. No difficulty was experienced in achieving control of wall thicknesses of the order of 0.1 in., and several complex vane designs were successfully cast with columnar grains throughout the airfoil and platforms. A typical example is shown in Fig. 5.

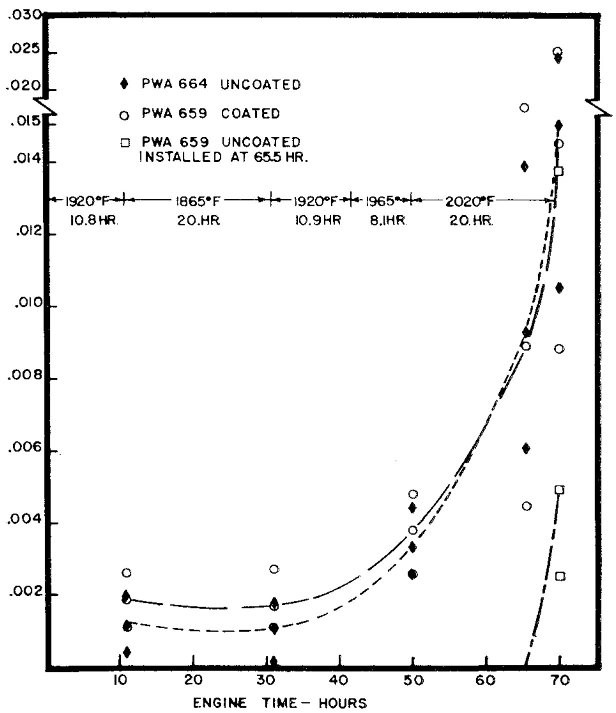


Fig. 4 Summary of blade growth with time of uncoated PWA 664, coated PWA 659, and uncoated PWA 659 first-stage blades.

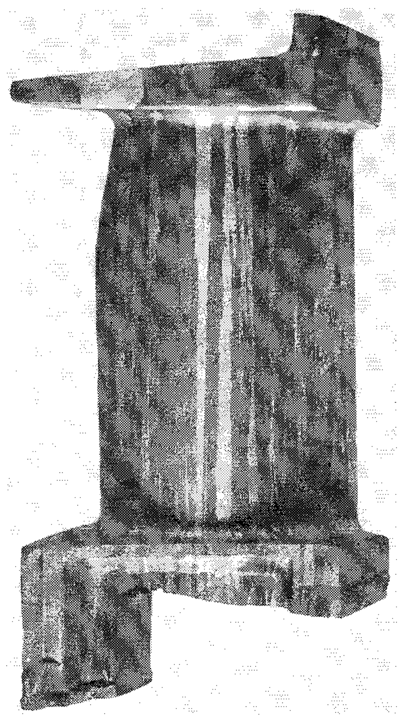


Fig. 5 Directionally solidified PWA 664 hollow-cored, cast-to-size JT3C-12 vane in macroetched condition showing columnar grain structure.

Several thousand gas-turbine vanes have been supplied by Thompson Ramo Woolridge (Metals Division) for rig testing, engine testing, and service testing; some of these were used in the following test.

Engine Testing of Vanes

Twenty-two PWA 664 uncooled JT8D first-turbine vanes were machined and coated with PWA-47-14L. The PWA 664 vanes, together with similar vanes of a comparative material, were assembled in alternate positions in an experimental JT8D test engine.

The test engine was mounted in an experimental sea level test stand and, upon completion of preliminary check runs, endurance testing was commenced. A total of 49.5 hr of endurance, 4.9 hr of which were at 1900°F turbine inlet temperature, were accumulated during the first phase of testing. This phase of the endurance test conformed to the requirements of the standard Federal Aviation Agency (FAA) cycling procedures. Each cycle encompassed various power setting changes during which time 12 accelerations from idle to takeoff power were made. After partial disassembly for a hot section inspection, a further 28.5 hr of the same type of endurance testing were added, 2.2 hr of which were at a 1850°F turbine inlet temperature.

A second hot section inspection was made before the second phase of the endurance test was commenced. The engine was then reassembled and the second phase of the endurance test was commenced. During this test of 500 cycles, 41.67 hr of endurance were run; 8.8 hr of this cyclic endurance were run at 1880°F turbine inlet temperature. Each of these 5-min duration cycles was comprised of approximately 1 min at takeoff power, 2 min at idle, 10 sec at 1.3 exhaust pressure ratio (EPR)¶ (reverse) and the remainder of the time at idle. A two-step power lever manipulation was employed during each of the accelerations from idle to takeoff to simulate a rolling takeoff. The engine was accelerated from idle to 1.4 EPR in ten sec or less, then accelerated from that point to the take-

¶ An engine pressure ratio of approximately 1.3 simulates conditions during application of thrust reversers.

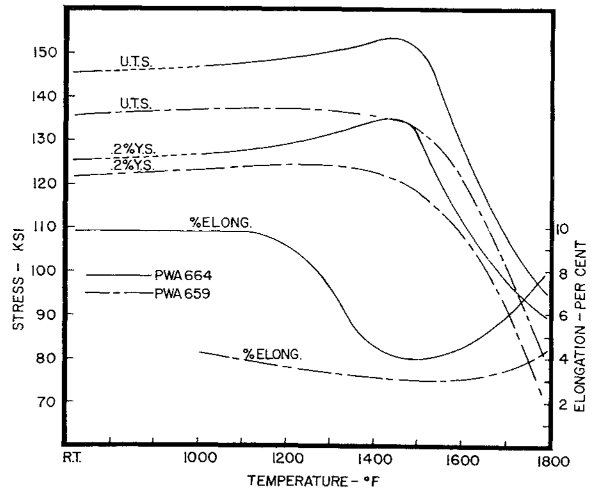


Fig. 6 Summary of the tensile properties of PWA 664 and PWA 659.

off EPR in ten sec or less. The throttle was then locked for 50 sec duration prior to deceleration to idle. Following completion of the 500-cycle test and subsequent hot section inspection, the engine was dismantled for replacement of first-stage turbine blades and combustion chambers.

Further endurance testing was continued after reassembly until 500 additional 5-min cycles, 41.67 hr, of endurance were accumulated, including 8.3 hr at 1890°F turbine inlet temperature. All the first-stage turbine vanes were then removed from the engine.

The post-test condition of the vanes generally was good, with the exception of the few located in the normally hotter burner positions, which did show a degree of distress. Measurement of trailing edge bow resulted in an average value of 0.015 in., indicating bow resistance far superior to Bill-of-Material PWA-653 material (WI-52), which under similar conditions would be expected to bow an average of 0.24 in. Because of practical considerations an A:B, B:C comparison was conducted to determine the A:C comparison. Subsequent in-flight service tests confirm this comparison. No transverse cracks were observed in any of the PWA 664 vanes, indicating that the material possessed the desired combination of bow resistance and thermal shock resistance.

Eight of the vanes contained radial cracks and all vanes had some degree of erosion present. The degree of distress was observed to be dependent on vane position relative to the burner can hot spots. Post-test laboratory examination revealed that the mode of failure was cracking along the columnar grain-boundaries. Microstructural examination of parts showing distress revealed microstructural features consistent with metal temperatures in excess of 2200°F. Burner development engine testing of specially instrumented combustion chambers similar to the experimental scheme used during the engine test indicated that chambers produced a 300°F average to maximum temperature spread in agreement with the microstructural observations made on distressed parts. From the results of the completed engine test, however, it was concluded that PWA 664 as a vane material displayed a degree of durability in the JT8D engine which was consistent with the anticipated performance based on previous rig testing and laboratory evaluation. It was recommended that, in view of its performance at elevated turbine inlet temperatures, the PWA 664 material be further engine tested, including service tests, to more fully document its potential. Four other commercial and military engine models as well as other JT8D engines containing PWA 664 vanes have been tested or are in some stage of testing in addition to the JT8D test just described. The results obtained from these tests were consistent with the behavior already demonstrated. A number of half sets of PWA 664 vanes are now being in-flight service tested in JT8D engines. One engine has already accumulated approximately 1572 hr of service time with no distress in the PWA 664 vanes. Twenty half sets of PWA 664 vanes have been delivered to the airlines, and a total of 13,625 hr of in-flight service time has been accumulated.

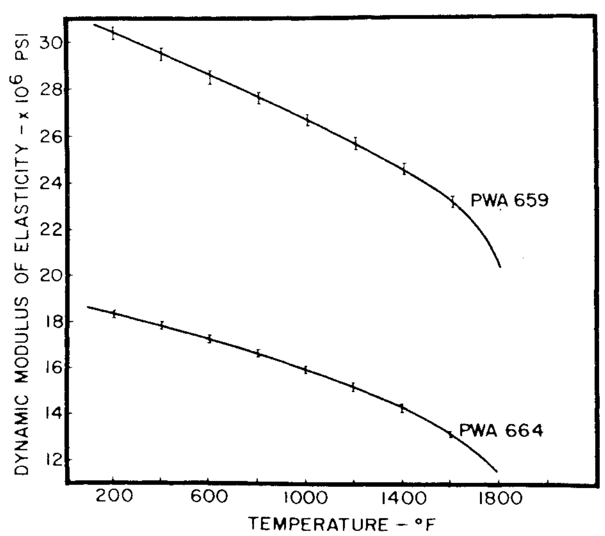


Fig. 7 Variation of the dynamic moduli of PWA 664 and PWA 659 with temperature.

Laboratory Properties Related to Turbine Blade and Vane Service

The following results, obtained by mechanical and rig testing, supplied the supporting information necessary to the early engine testing of PWA 664.

Tensile strength

The tensile properties of the two materials are compared in Fig. 6. The figure shows that a moderate increase in strength is realized and also that a substantial increase in ductility is obtained. The marked increase in low- and high-temperature ductility in PWA 664 accentuates the minimum in ductility at 1500°F. This minimum, however, still has a value in excess of the average values of PWA 659. It is notable that the maximum in tensile strength coincides with the minimum in tensile ductility, a common effect observed in wrought nickel-base superalloys where the values of ductility are sufficiently high to observe the effect.

Dynamic modulus

During the tensile testing of PWA 659 and PWA 664, it was observed that there were considerable differences in the static elastic modulus of the two materials (Table 2). This may be expected as a result of the preferred orientation of PWA 664. To determine the magnitude of the differences in the dynamic elastic moduli, the Materials Testing Laboratories of Magnaflux Corporation were contracted to perform determinations on four specimens, two each of PWA 659 and PWA 664. The tests were performed in the Magnatest FM-500, a commercially available rig. In this rig, moduli determinations are made by measuring the fundamental transverse frequency of the specimen supported in a furnace as a free-free beam. The results of the test are shown in Fig. 7. These do not include

Table 2 Static modulus of elasticity

Temperature	70°F	1400°F	1800°F
PWA 659	29.8	24.1	20.7
PWA 664	21.2	15.2	11.8
PWA 653	29.1	21.3	13.4

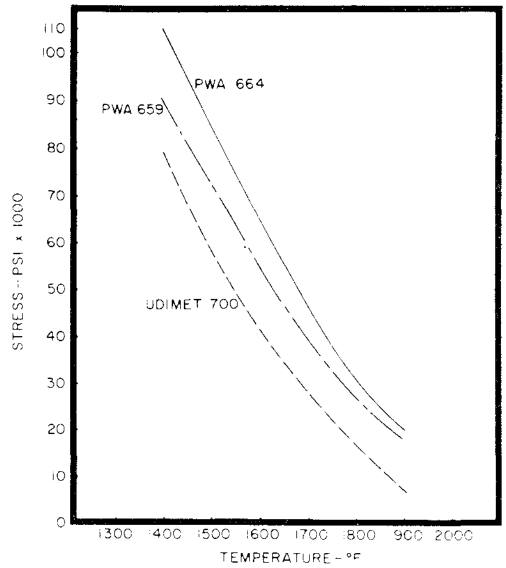


Fig. 8 Comparison of PWA 664, PWA 659, and PWA 1008 (Udimet 700) in stress to produce rupture in 100 hr correlated with temperature.

correction factors to allow for rotary inertia, shear, or thermal expansion effects, since calculations showed such effects to be negligible. For three of the specimens, first and second overtones were measured in order to assess the effect of frequency on the dynamic modulus. Within the range of frequencies of the order 3×10^3 to 16×10^3 cps, the dynamic modulus varied by only 10%, being lower at the higher frequency.

Resonant frequency

The effect of dynamic modulus on the natural resonant frequency of JT4 turbine blades was determined prior to fatigue testing. The values obtained at 70°F indicate the resonant frequency of the PWA 664 blades was approximately 82% of that of the PWA 659 blades, in agreement with the ratio of the square roots of their moduli.

Creep and stress-rupture

At all temperatures tested PWA 664 was shown to be superior to PWA 659, the most significant improvement being observed at 1400°F. A demonstrative comparison may be made in a test at 1400°F and 100,000 psi, where a PWA 664 specimen is shown to have a life of at least 100 hr. A PWA 659 specimen will usually break on loading or at the most break

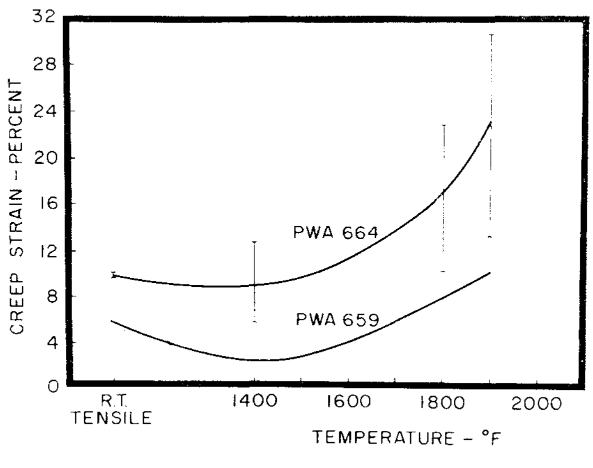


Fig. 9 Average rupture elongation of creep-tested PWA 664 and PWA 659 correlated with temperature showing that the minimum values of PWA 664 were greater than the average values obtained with PWA 659 at all temperatures.

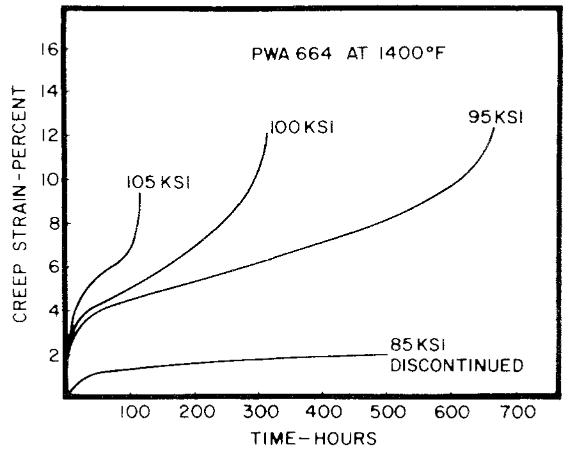


Fig. 10 Creep behavior of PWA 664 tested at 1400°F.

within 10 hr. A summary of the stress to produce rupture in 100 hr is correlated with temperature in Fig. 8. The most significant feature of the stress-rupture tests was the rupture elongations. The results from tests over a wide range of stress and rupture life are shown in Fig. 9. It may be observed that the minimum elongation value obtained at 1400°F lies at approximately 5% and that the minimum values, at all temperatures, were greater than the average values obtained with PWA 659. Proof of the existence of third-stage creep is shown in Fig. 10 and is observed at all temperatures tested, a desirable feature of a material to be used in a gas turbine because it serves to indicate the approach of the end of the blades' useful service life. Furthermore, Fig. 11 shows that at 1800°F PWA 664 not only has almost double the life and elongation of PWA 659 under the same conditions of temperature and stress, but also half the minimum creep rate. In all of the foregoing data, the properties measured were obtained by testing specimens such that the stress axis was parallel to the columnar grain axis. Test peices also were made with the stress axis normal to the columnar grain axis, and, since a transverse section of PWA 664 has the appearance of randomly oriented equiaxed grains, it would be expected that the properties obtained should be equivalent to that of conventionally cast material. The transverse stress-rupture properties of PWA 664 are in fact about the same as conventionally cast PWA 659.

Creep testing at 2000°F

Creep testing at 2000°F has shown that both the time to 1% creep and rupture life of PWA 664 are superior to PWA 653.

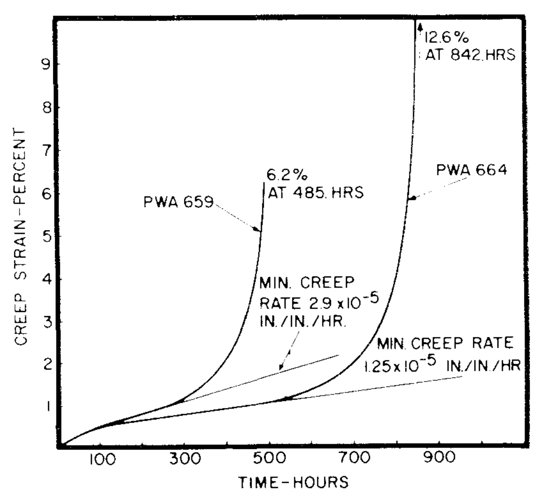


Fig. 11 Comparative creep behavior of PWA 664 and PWA 659 at 1800°F and 20,000 psi.

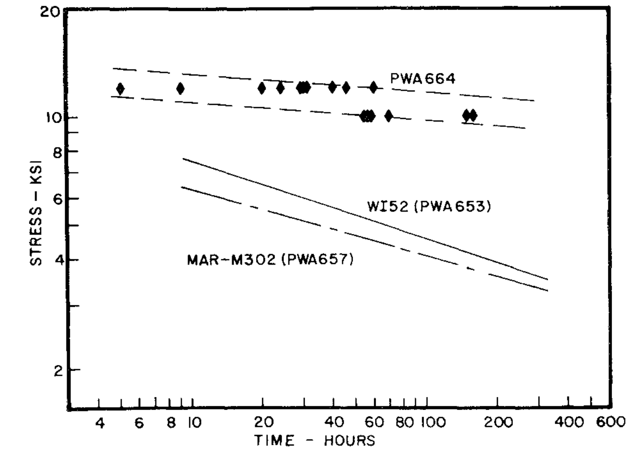


Fig. 12 Comparison of the times to produce 1% creep at 2000°F of the three materials PWA 664, PWA 657, and PWA 653 at various stresses.

The results shown in Fig. 12 indicate that bowing would be substantially reduced with this material.

Ballistic impact

A possible cause of failure of gas-turbine blades is that due to foreign object damage PWA 659 and PWA 664 turbine blades were tested in a 1750°F ballistic impact test using a 0.64-g pellet at 1000 fps. Comparison of the two materials after test shows a marked and desirable improvement in the PWA 664 material. Impact of the pellet on a PWA 659 turbine blade results in severe cracking of the blade on the opposite side, whereas the PWA 664 blade deforms without cracking. It appears also that, when the pellet passes through the blade, considerably less damage results in the PWA 664 blade than in the PWA 659 blade.

Impact and slow bend

Further evidence of the effect of the process on the alloy Mar-M200 was obtained in a slow bend test on a turbine blade casting. The result is shown in Fig. 1. The results of notched and unnotched Izod impact testing indicated, however, that the process has little effect on the inherent toughness of the material in the presence of a notch. In the absence of a notch, the effect of transverse grain-boundaries was shown to be detrimental.

Fatigue

Root and airfoil fatigue tests were carried out on PWA 659 and PWA 664 JT4 turbine blades. Because the blade was designed with a heavy root, it was found to be impossible to induce failure in the root during a root fatigue test, failure occurring consistently in the airfoil. A comparison may only be made, therefore, between the airfoil fatigue tests. The values indicated that no loss in fatigue strength results either with the preferentially oriented columnar-grained structure or from the application of the PWA-47-14L coating to PWA 659.

Thermal shock

A series of cast and machined PWA 659 and PWA 664 JT4 turbine blades were subjected to thermal shock in a test rig. The test results are shown in Table 3 together with the conditions of the test. The test confirmed that PWA 659 was susceptible to thermal shock in common with most other conventionally cast nickel-base superalloys. On the other hand, it was demonstrated that PWA 664 was thermally shock resistant in a gaseous environment even at temperatures approaching the incipient melting point of 2265°F. The tests showed that, under conditions of thermal shock, cracks in PWA 659 blades were propagated if the test was continued. Figure 13 shows the condition of a PWA 659 turbine blade after 1400 cycles to be compared with a PWA 664 blade that has survived 1400 cycles. Furthermore, a second PWA 664 blade survived the same 1400 cycles and, in addition, 115 cycles at 2250°F and 51 cycles at 2300°F, without cracking. The temperatures quoted refer to the metal temperature measured by optical pyrometer to ±15°F. One of the PWA 664 blades was manufactured at the Thompson Ramo Wooldridge (Metals Division) facility; an indication of the reproducibility of the process. A PWA 653 vane tested under similar conditions survived only 540 cycles at 2000°F before cracking. Undoubtedly, the lower elastic modulus (see Table 2) is partially responsible for the greater resistance to thermal shock, since the elastic portion of the thermally induced stress is equal to $E\alpha\,\Delta T$, where E is the modulus of elasticity, α is the linear coefficient of expansion, and ΔT is the temperature difference.

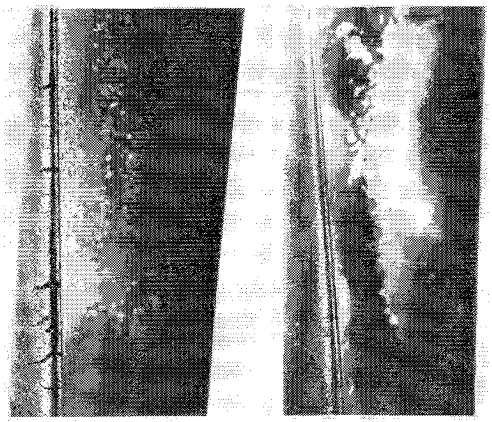
Physical Metallurgy

In order to determine the reason for the improvement in properties imparted by the directional solidification process, a study of the structure of the two materials was made. In cast metals and alloys there are two types of grains, described as equiaxed and columnar. The mechanism of formation of these two types of grains depends on many variables, including metal composition, pouring temperature, mold temperature and temperature gradient, and mold size and shape.

An equiaxed grain is usually described as having an axial ratio approximately equal to 1 and forms as a result of the uniform three-dimensional growth of a nucleus within the melt. A columnar grain, however, usually has an axial ratio much greater than 1 and is more often nucleated at a surface. The crystallographic orientation of each type of grain in a

Table 3 Summary of thermal shock data

Material	Specimen	Cycles at: 2000°F	2100°F	2200°F	Total cycles	Condition
PWA 659	JT4 blade	300	...	...	300	Cracked
PWA 659	JT4 blade	600	400	...	1000	Cracked
PWA 659	JT4 blade	600	200	...	800	Cracked
PWA 659	JT4 blade	300	...	...	300	Cracked
PWA 659	JT4 blade	300	...	...	300	Cracked
PWA 659	JT4 blade	500	...	...	500	Cracked
PWA 664	JT4 blade	600	400	400	1400	No damage
PWA 664	JT4 blade	600	400	400	1400	No damage
PWA 664	Coated JT4 blade	600	400	400	1400	No damage
PWA 664	JT8D vane	600	400	400	1400	No damage
PWA 664	JT8D vane	600	400	400	1400	No damage
PWA 664	JT4 blade	600	400	400 + 115 cycles at 2250°F + 51 cycles at 2300°F	1566	No damage



a) b)

Fig. 13 a) Uncoated PWA 659 JT4 first-stage turbine blade, tested in a thermal shock rig, after 600 cycles at 2000°F, 400 cycles at 2100°F, and 400 cycles at 2200°F. One crack was visible after the first 800 cycles. b) Uncoated PWA 664 JT4 first-stage turbine blade, tested in a thermal shock rig, after 600 cycles at 2000°F, 400 cycles at 2100°F, and 400 cycles at 2200°F. The blade shows no cracks.

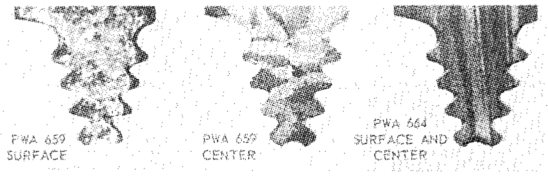


Fig. 14 Comparison of the macrostructures of the surface and center sections of a PWA 659 JT4 first-stage turbine blade with the macrostructure of a PWA 664 JT4 first-stage blade root section.

casting may be random except under particular conditions when a columnar grain may have a preferred orientation. Confusion arises, therefore, when the definitions described previously are applied to the macrograin structure of a turbine blade. The structure produced by conventional casting in shell molds is often described as producing either a random grain or an equiaxed grain. The latter case usually refers to the control of grain size and shape by control of metal and mold temperature with or without melt or mold-surface innoculation. In the absence of control a random assembly of grains with large variations in size and shape is produced. The macroetched surface of a casting produced under controlled conditions gives the appearance of a uniform equiaxed grain structure both in the thin and thick sections. Sectioning of such a casting reveals, however, that the grains have grown normal to each mold wall, impinging at the center of the casting. Where the thickness of the casting is approximately twice the grain diameter, the grains have an axial ratio of 1 and could therefore be described as equiaxed. However, when the surface grain diameter is small and/or the thickness of the casting is great, then the axial ratio of the grains is greater than 1. The mechanism of solidification of an alloy in a shell mold cast under controlled conditions may therefore be described as the uniform nucleation of randomly oriented columnar grains at a mold surface and their growth perpendicular to all mold surfaces. In the majority of cases, the length of the columnar grain is governed only by the width of the mold cavity, such that growth is restricted by impingement of the grains with similar grains growing from an opposite face. Exceptions occur in thicker sections where the nucleation of true equiaxed grains may occur in the melt. The net result is nevertheless a preponderance of transverse grain-boundaries.

The grain structure of PWA 664 material refers to a particular type of columnar grain, that is, preferentially oriented. It is found that, under the conditions of a steep temperature gradient such as may be imposed by means of a water-cooled copper chill, the growth of grains with a ⟨100⟩ orientation is preferred.[5] Thus, if molten metal is poured into a turbine blade mold held at a temperature above the melting point of the metal and whose base is replaced by a water cooled copper chill, columnar grains with the ⟨100⟩ preferred orientation grow only from the base. The difference in macrostructure between PWA 659 and PWA 664 is well illustrated by a macrophotograph of the surface of a PWA 659 blade casting as shown in Fig. 14 which may be compared with a section through the center of the same casting and a similar section through a PWA 664 blade casting

Examination of photomicrographs taken at similar locations from longitudinal sections of the roots of PWA 664 and PWA 659 blade castings indicate that the most notable differences are: 1) the random orientation of the grain in the PWA 659 casting compared to the vertically oriented grain in the PWA 664 casting, and 2) the large amount of microporosity in the PWA 659 casting and its absence in the PWA 664 casting.

Conclusions

A casting process has been developed which results in longitudinal columnar grains with a preferred orientation, thereby eliminating the presence of transverse grain-boundaries in gas-turbine hardware. Both gas-turbine blades and vanes have been cast to size in several complex shapes.

PWA 664 in the uncoated condition has been shown to have a longer life than coated PWA 659 when compared as turbine blades in an experimental engine. PWA 664 demonstrates more thermal shock resistance and bow resistance than PWA 653 when tested as vanes in an experimental engine.

PWA 664 has been shown by laboratory tests to be superior in strength and thermal shock resistance to PWA 659 and PWA 653 (WI-52) and yet retains adequate ductility at all temperatures. The tests have shown that improvement in some properties is made without loss in others; for example, the thermal shock resistance of Mar-M200 as PWA 644 is superior to the alloy as PWA 659 and yet the creep strength also is improved.

The improvement in properties resulting from the application of the directional solidification process to the alloy Mar-M200 is caused by the elimination of transverse grain-boundaries, the production of a preferred orientation, and the resulting change in modulus of elasticity.

The PWA 664 process offers a new approach to the development of superalloys with strengths suitable for increased service temperatures without the loss of other desirable properties. For example, the alloy modification of high-strength superalloys may be directed at improvement in oxidation resistance with less chance of compromising ductility and thermal shock resistance.

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