THE DEVELOPMENT OF SINGLE CRYSTAL SUPERALLOY TURBINE BLADES

by

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Single crystal superalloy turbine blades have recently entered production for JT9D commercial engine applications. This significant technical advance was made possible by the development of an alloy with improved properties and the development of a production casting process. The absence of grain boundary strengthening elements provided considerable alloying and heat treatment flexibility that resulted in single crystal Alloy 454 with an outstanding balance of properties. Major improvements in temperature gradients, the use of helical grain selectors, and the incorporation of these advances into existing vacuum furnaces have led to the rapid development of a production casting capability.

INTRODUCTION AND BACKGROUND

Improvements in gas turbine engine thrust, fuel consumption and durability over the years have been closely related to improvements in turbine airfoil materials and cooling systems. The decade of the 60's was characterized by the use of high strength conventionally cast alloys such as B-1900 + Hf, IN100 and Rene' 80. Turbine airfoil materials advances in the late 60's and in the 70's came chiefly through the development and application of directionally-solidified (D.S.) turbine airfoils(1,2)(Fig. 1). The introduction of D.S. turbine blades and vanes by Pratt & Whitney Aircraft (P&WA) in military engines in 1969 and in commercial engines in 1974 resulted in significant increases in allowable metal temperatures and rotor speeds. This paper describes the development and application of the next major advance in turbine airfoil materials – Single Crystals.

CONVENTIONAL CASTING   DIRECTIONAL SOLIDIFICATION

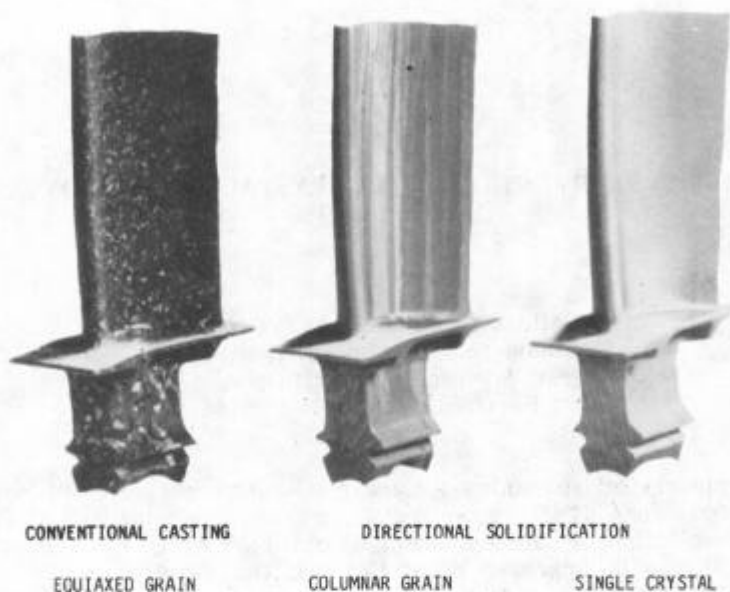EQUIAXED GRAIN   COLUMNAR GRAIN   SINGLE CRYSTAL

Fig. 1   Advances in turbine airfoil materials.

Early development work on single crystal turbine airfoils was conducted at P&WA in the mid-60's in parallel with the D.S. effort(2,3). This effort focused on making and evaluating single crystals of existing superalloy compositions such as MAR-M200. These single crystals had no greater creep strength, axial thermal fatigue resistance or oxidation resistance than D.S. MAR-M200, but had improved transverse strength and ductility compared to the early D.S. MAR-M200 alloy. With the addition of hafnium to D.S. MAR-M200 in 1969(4), transverse grain boundary strength and ductility were significantly improved. Work on single crystals was discontinued at this time because they offered no significant improvements in properties over D.S. and they were more expensive.

SINGLE CRYSTAL ALLOY DEVELOPMENT PHILOSOPHY

In 1975, heat treatmemt studies on D.S. MAR-M200 + Hf showed that creep strength was controlled by the volume fraction of the fine gamma prime phase and that the key to maximizing this phase was increasing the alloy's incipient melting and solution heat treatment temperatures(5). This work and early confirmatory work on single crystal MAR-M200 without any grain boundary strengthening elements(6) in 1976 provided an alloy design approach with the following guidelines:

o   The alloy would contain no intentionally added grain
     boundary strengthening elements (boron, carbon, hafnium
     and zirconium); this would provide a high incipient melting
     temperature (>1288°C, 2350°F).
o   A high gamma prime solvus temperature (>1260°C,
     2300°F), lower than the incipient melting temperature,
     would provide high creep strength.
o   A high solution heat treatment temperature, between the
     gamma prime solvus and the incipient melting
     temperatures, would provide improved properties by
     complete solutioning of the gamma prime phase and by
     significant reduction in dendritic segregation.

These guidelines were used to address the challenge of
developing a new turbine blade material. The critical properties
required by turbine blades are: *creep strength, thermal fatigue
strength, oxidation resistance and hot corrosion resistance.* Since
D.S. MAR-M200 + Hf possesses very high levels of creep and
thermal fatigue strength, further improvements in metal
temperature capability have to result from increases in all four
critical properties. The formidable challenge of the single crystal
program was to develop an alloy with a balanced level of properties
greater than those of all existing superalloys.

SINGLE CRYSTAL ALLOY 454

Based on the above guidelines and 15 years of turbine blade
alloy development experience, an extensive single crystal alloy
development effort was undertaken. The alloys considered contained
a high level of tantalum, as this element alone among the third
series transition elements confers both high levels of creep strength
and oxidation resistance. Tantalum also significantly reduces the
tendency toward a serious casting defect, referred to as
"freckling"(7). Sufficient chromium and aluminum levels were
maintained to ensure that the alloy would be an alumina former. To
promote excellent hot corrosion resistance, the chromium level was
set high and deleterious elements such as molybdenum and vanadium
were avoided.

The alloy that showed the best balance of the four critical
properties was Alloy 454, whose composition and that of D.S.
MAR-M200 + Hf are given in Table 1. The chemistry of Alloy 454 is
very different from that of existing superalloys because of the
absence of all grain boundary strengthening elements and the
significant use of tantalum. The compositional simplicity is also
evident, with Alloy 454 containing six alloying elements and D.S.
MAR-M200 + Hf containing ten.

Table 1. Alloy Compositions (weight percent)

	Ta	W	Cr	Al	Ti	Cb	Co	Hf	C	B	Zr	Ni
Alloy 454	12	4	10	5	1.5	--	5	--	--	--	--	Bal.
D.S. MAR-M200+ Hf	--	12	9	5	2	1	10	1.8	0.14	0.02	0.08	Bal.

A solution heat treatment for four hours at 1288°C (2350°F) completely solutions all the coarse secondary gamma prime and most of the eutectic phase and provides significant compositional homogenization of the alloy on a microscale (Fig. 2). A two–step aging heat treatment of four hours at 1079°C (1975°F) and 32 hours at 871°C (1600°F) is used to form 65 volume percent of a cuboidal gamma prime precipitate of a size less than 0.3 microns.
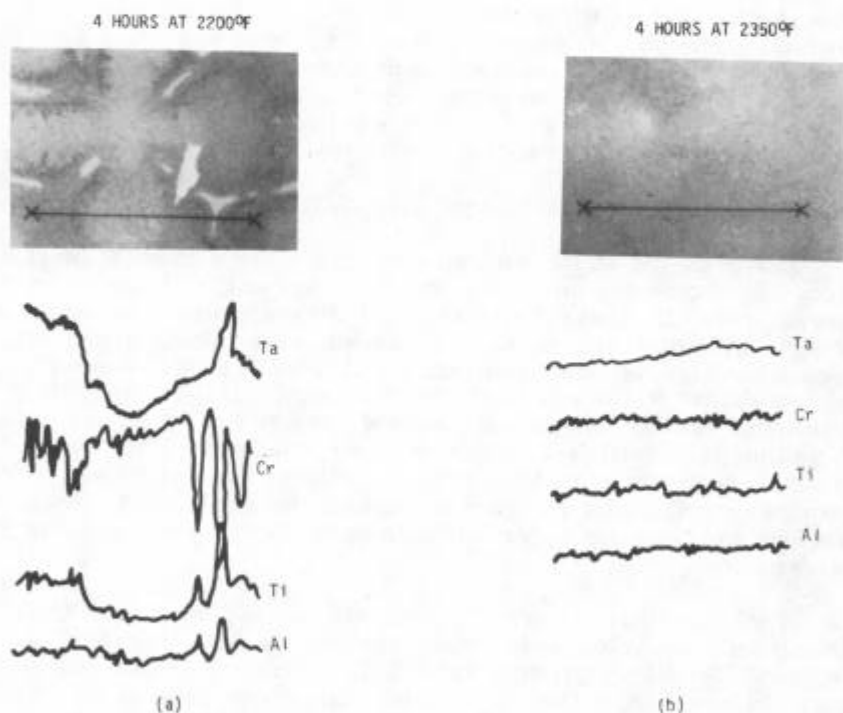

Fig. 2   Alloy 454 microstructure with microprobe traces after a) 2200°F/4 hours used for D.S. alloys and b) 2350°F/4 hours.

ALLOY 454 PROPERTIES

Hundreds of creep-rupture tests have been conducted over the temperature range of 760°C (1400°F) to 1204°C (2200°F) on specimens machined from turbine blades and cast test bars. The results, summarized in Fig. 3, show that Alloy 454 has a 25°C (45°F) to 50°C (90°F) temperature advantage over D.S. MAR-M200 + Hf, the strongest production blade alloy. A 25°C (45°F) improvement in metal temper-

Fig. 3 Creep strength of single crystal Alloy 454 and D.S. MAR-M200 + Hf.

ature capability corresponds to a three-fold improvement in life. The creep strength advantage at low temperature is associated with the homogeneous microstructure and the high volume fraction of fine gamma prime. The even greater strength advantage at higher temperature is associated with the retention by Alloy 454 of a higher volume fraction of gamma prime with increasing temperature compared to D.S. MAR-M200 + Hf.
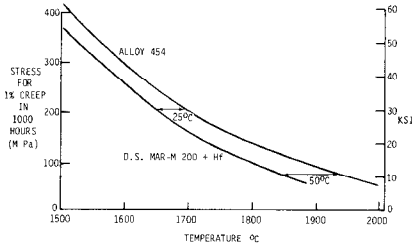
Thermal fatigue cracks in many advanced cooled turbine blades initiate in the coating at the blade leading edge and propagate into the superalloy. Fig. 4 shows the results of a laboratory strain-controlled thermal-mechanical fatigue test that simulates this blade cracking(8). The thermal fatigue life of NiCoCrAlY coated Alloy 454 is 1.8X or 56°C (100°F) greater than that of NiCoCrAlY coated D.S. MAR-M200 + Hf. Both alloys

Fig. 4 Thermal fatigue proper-ties of Alloy 454 and D.S. MAR-M200 + Hf.

have outstanding thermal fatigue properties compared to conventionally-cast alloys because of their 40 percent lower elastic modulus. The additional thermal fatigue strength of Alloy 454 is associated with a slower crack growth rate which in turn is related to the alloy's higher yield strength and improved oxidation resistance.
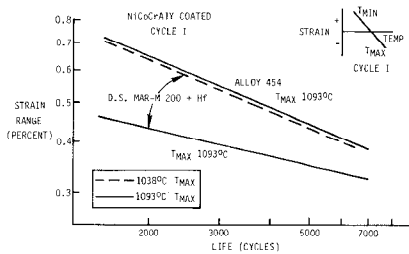
The oxidation resistance of a superalloy is primarily related to its composition and the nature of the oxide formed(9). Fig. 5 shows that the oxidation resistance of Alloy 454, which forms a continuous protective alumina layer, is at least 75°C greater than that of D.S. MAR-M200 + Hf which does not form a continuous alumina layer. The improved oxidation properties derive from the relatively high levels of chromium and aluminum, the use of tantalum rather than tungsten as the principal strengthening element and the reduced level of titanium. Alloy 454 also exhibits similar improvements in NiCoCrAlY coated oxidation resistance because of the improved interdiffusional characteristics of the electron beam vapor deposited coating on the single crystal compared to D.S. MAR-M200 + Hf (Fig. 6).
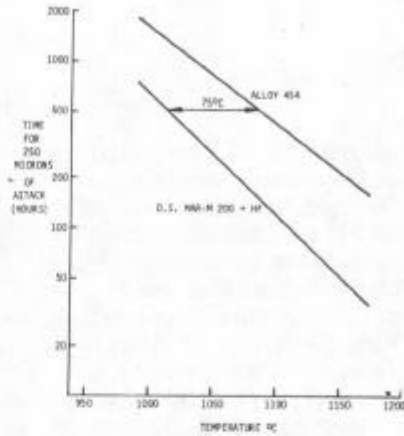

Fig. 5 Oxidation resistance as a function of temperature for Alloy 454 and D.S. MAR-M200 + Hf.
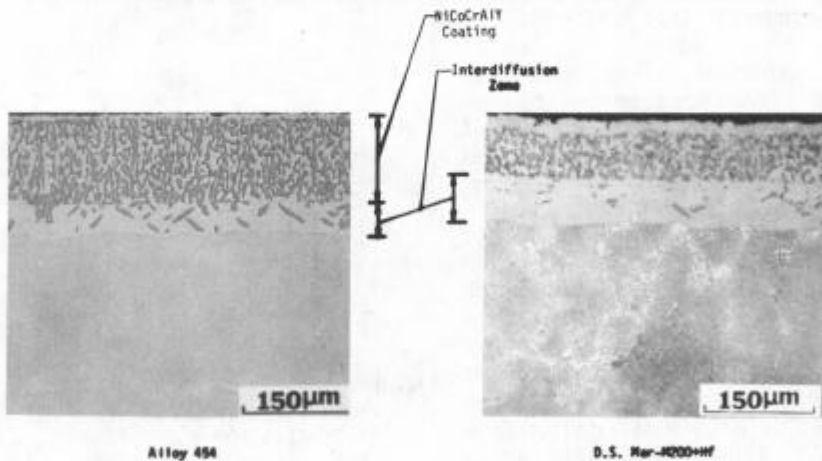

Fig. 6 Interdiffusion zone thickness after 50 hours at 2100°F for Alloy 454 and D.S. MAR-M200 + Hf.

Advances have been made in the fundamental understanding of hot corrosion mechanisms in superalloys and its dependence on composition(10). Sulfur in the fuel and salt in the air contribute to the formation of molten sodium sulfate on the blade surface. Certain elements in the alloy, such as molybdenum and vanadium, dissolve in the sodium sulfate and prevent the formation of a protective oxide film. Fig. 7 shows the improved hot corrosion resistance of Alloy 454 which is associated with a higher level of chromium than found in D.S. MAR-M200 + Hf and the absence of molybdenum, vanadium or high levels of tungsten that are contained in most superalloys.
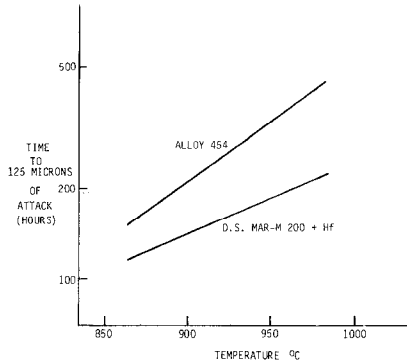

Fig. 7   Hot corrosion resistance of Alloy 454 and D.S. MAR-M200 + Hf.

SINGLE CRYSTAL TURBINE BLADE CASTING DEVELOPMENT

The ability to cast production quantities of single crystal turbine blades is an important part of the overall single crystal development program. This effort relied heavily on the ten years of production experience obtained on columnar-grained turbine blades. However, the additional requirements for making advanced, cooled single crystal turbine blades necessitated technical innovations particularly in the areas of obtaining high temperature gradients during solidification and achieving single crystallinity throughout the component.

The columnar-grain and single crystal casting processes are shown schematically in Fig. 8. In each case, molten superalloy is poured into a ceramic mold seated on a water cooled copper chill. Grains are nucleated on the chill surface and grow in a columnar manner parallel to the unidirectional temperature gradient. These columnar-grains fill the turbine blade cavity for the D.S. process in Fig. 8a. For the single crystal case in Fig. 8b, a number of grains enter the bottom of the helical grain selector, one grain emerges from the top of the selector, and this grain fills the entire mold cavity.

Columnar grain casting process
(a)

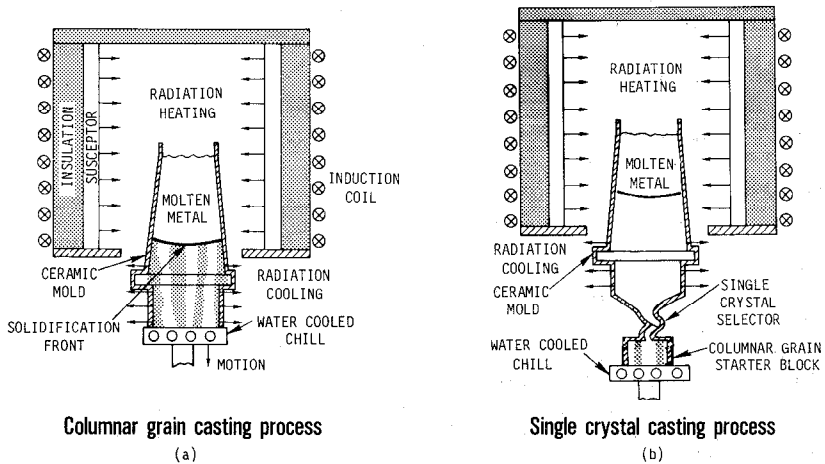Single crystal casting process
(b)

Fig. 8   Schematic drawing of directional solidification process for a) columnar-grained and b) single crystal turbine blades.

The temperature gradient in the nucleation chamber is controlled by the chill, the molten metal superheat and the mold temperatures. The mold temperature is typically 1500- 1600°C (2732-2912°F), some 25-100°C (45-180°F) higher than for the columnar-grained growth process. The higher temperatures prevent the nucleation of spurious grains during the pour, ahead of the advancing dendritic growth interfaces or on the mold surface. At the water cooled copper chill many grains are nucleated with essentially random orientations. Grain texture and rocking curve analyses indicate that the <111> oriented grains are quickly overgrown by those with <110> and <100> orientations. The latter two orientations have more similar maximum growth rates and it requires at least 2 cm (0.75 inch) of growth before more than 90 percent of all grains are within 15° of the <001> orientation.

As solidification proceeds, two to six grains enter the helix, or grain selector, as shown in Fig. 9. Some grains are physically blocked from entering the helix and the one or few that survive have their horizontal <100> dendrites most favorably positioned to enter the helix. After one or two turns of the helix only one crystal survives. The helix wire diameter typically varies from 0.3 to 0.5 cm (0.1 to 0.2 inch) with the exact size chosen to give the required heat flow and mold integrity. A helix with a circular cross-section is used instead of a series of ramps with a rectangular cross-section in order to minimize grain nucleation at sharp edges.

When solidification proceeds into the component a number of cross-sectional area changes occur, such as from the airfoil to the platform and from the platform to the blade root. The heat flow has to be managed to keep the solidus and liquidus isotherms near horizontal and near the baffle during these cross-sectional changes in order to prevent grain nucleation. The interfaces are kept near the baffle by proper management of heat flow through baffle design, mold thickness and withdrawal rate schedule.
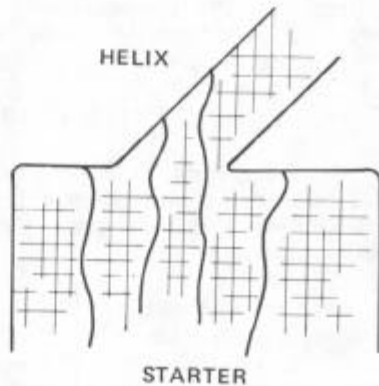

Fig. 9   Grains entering the helix.

Using the above procedures, a large number of single crystal turbine blades and vanes have been cast (Fig. 10) and a production capability has been established. The single crystal production process uses the same vacuum furnaces as for columnar-grain
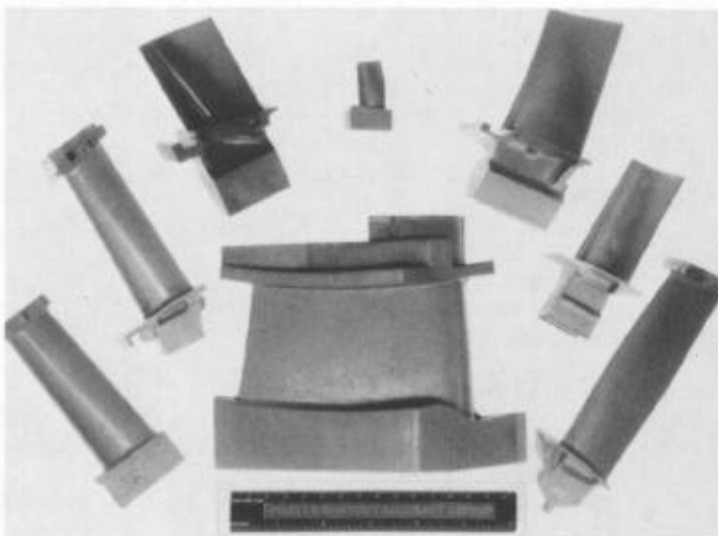

Fig. 10   Many different single crystal turbine blades and vanes have been cast.

castings, but the temperature gradients in the furnaces have been increased significantly from about 36 to 72°C/cm (165 to 329°F/in) by the procedures just described.

SINGLE CRYSTAL TURBINE BLADE APPLICATIONS

All the critical property advantages of Alloy 454 turbine blades have been demonstrated in a large series of JT9D, F100 and PT6 (T400-WV-402) engine tests that have accumulated over 20,000 engine endurance cycles.

On the basis of these demonstrated property advantages and the developed production casting practice, single crystal Alloy 454 has been chosen as the material for the first stage turbine blade in the JT9D-7R4 series of engines that will power the Boeing 767 and the Airbus Industries A310 aircraft. Engine certification and initial production shipments are planned for July of 1980. Alloy 454 turbine blades have also been selected for the fuel conservative JT10D commercial engine presently under development and this single crystal alloy is being considered for advanced models of other commercial and military engines.

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