CM 186 LC® ALLOY
SINGLE CRYSTAL TURBINE VANES

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ABSTRACT

There is a need to introduce advanced turbine technology at reduced cost. SX superalloy vanes demonstrate excellent engine performance and durability benefits compared to their polycrystalline counterparts. However, their manufacturing cost can be prohibitive due to low casting and solution heat treatment yields due to rejectable grain defects. High purity (carbon and boron free), ultra high creep and fatigue strength SX alloys are limited to low angle boundaries (LABs) normally not exceeding 6° in critical airfoil locations. Carbon (C) and boron (B) containing SX superalloys (Ross, et al., 1996) can accommodate low angle boundaries in the 9° - 12° range with an overall sacrifice in creep and fatigue properties. Aero engine vane segments with complex configurations, can result in not only LAB defects exceeding 9° - 12° but also high angle grain boundary (HAB) defects ≥ 15° occurring during the SX solidification process. This is further excaberated by recrystallised grains occurring during solution heat treatment from residual casting stresses and associated strain.

CM 186 LC® is a hafnium (Hf) containing nickel-base superalloy developed for directionally solidified (DS) columnar grain turbine airfoils. SX casting experience - development and production - has shown the alloy can be readily cast into aero turbine multi-airfoil segments. Mechanical property and turbine engine testing show the alloy can accommodate grain boundaries at least up to 30° resulting in high SX casting yields. The SX vane components are either used as-cast or approximately 50% partial solutioned which avoid any recrystallisation (Rx) problems. Component costs can be < 50% of that of a conventional high purity SX alloy.

Mechanical property, oxidation and coating performance characterisation studies on SX CM 186 LC (including DS test pieces) and turbine engine test and application experience show a 72°F (40°C) metal temperature capability improvement (thin wall) over DS MAR M 002 alloy.

NOMENCLATURE

B = boron
C = carbon
DA = double aged
DS = directionally solidified, columnar grain
ETOPS = extended over water, twin engine certification
HAB - high angle grain boundary
Hf = hafnium
ISA = International Standard Atmosphere (15°C)
La = lanthanum
LAB = low angle grain boundary
LCF = low cycle fatigue
Rx = recrystalised grains
RR = Rolls-Royce
RRA = Rolls-Royce Allison
SCFO = Single Crystal Foundry Operations
TBC = thermal barrier coating
TCP = topologically close-packed phase
TF = thermal fatigue
Y = yttrium
Zr = zirconium
γ' = gamma prime phase

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Presented at the ASME "Turbo Expo '99" Indianapolis, Indiana, USA, June 7-10 1999.

INTRODUCTION

Integrated superalloy/component design/manufacturing technology utilising materials systems approaches has made appreciable progress in the last 5-8 years. Turbine inlet temperatures at maximum power takeoff conditions now reach 3000°F (1650°C) for ETOPS certified large commercial turbofan engines utilising rhenium (Re) containing single crystal (SX) superalloys, 3D airfoil stress and aerodynamic design, advanced cooling schemes and thermal barrier ceramic coatings. Dual-wall cooling configurations giving further improvements to turbine engine efficiency will enter commercial airline service in the next 4-5 years.

Aero turbine engine test and service experience have already demonstrated the enhanced service life with SX vane segments when compared to their equiaxed, polycrystalline counter parts (Burkholder, et al., 1995). This improvement is brought about by the superior thermal fatigue, LCF, creep strength, oxidation and coating performance of SX superalloys and absence of grain boundaries in the SX vane segments. There is also a further very significant improvement of thin wall (cooled airfoil) creep properties of SX alloys compared to polycrystalline superalloys (Fig. 1). [Courtesy PWA]. DS columnar grain vanes are also used with success (Cetel, et al., 1992) but they are less advantageous than SX vanes due to the grain boundaries in the non-airfoil regions, particularly in the inner and outer shrouds of multiple airfoil segments, where the complex stress levels can be quite high. Multiple airfoil segments are of growing interest to turbine design engineers due to their potential for lower machining and fabrication costs and reduced hot gas leakage.

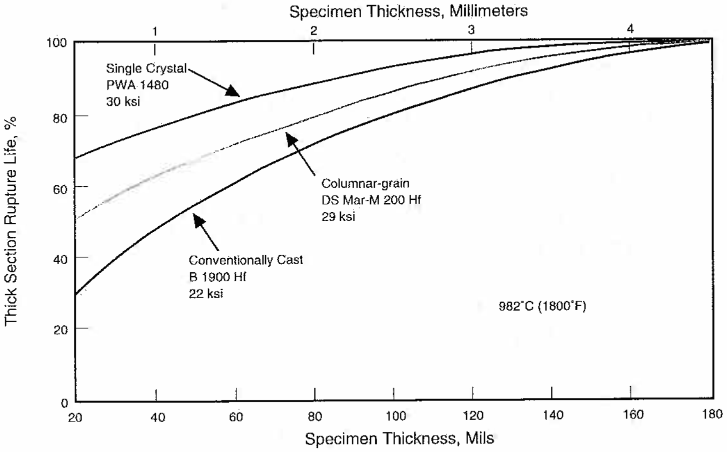

Figure 1. Single Crystal Superalloys retain a higher fraction of their thick section rupture life at thin sections below 150 mils. (.150") (3.8 mm) than polycrystalline superalloys. [Courtesy PWA].

The increased operating stress and turbine temperatures, combined with the demand for reduced maintenance intervals, can necessitate the enhanced properties and performance of SX Re containing superalloy vane segments. However, the rapid growth of the regional jet airliner market has created the need and objective of this work, for higher casting yields to lower component cost. To address this requirement, the concept to use CM 186 LC (Caruel, et al., 1998) SX vane segments was mutually developed and designed into the latest versions of the Rolls-Royce Allison (RRA) turbofan engines.

CM 186 LC is a highly alloyed cast superalloy with 3% Re and 70% volume fraction of the coherent γ′ precipitate strengthening phase. It was carefully designed to contain optimum amounts of C, B, Hf and Zr and consequent carbide and boride grain boundary phases to give good transverse creep-rupture strength, ductility and low cycle fatigue (LCF) properties in DS columnar grain turbine airfoils.

The manufacturing and design approach utilised in this program was as follows:-

1. "Seeded" SX casting technology is used to produce the SX vane segments.
2. The high creep strength, ductile, Re containing DS superalloy (CM 186 LC (Table 1)) with appreciable turbine engine service experience (McColvin, et al., 1997) is utilised, with no changes to alloy chemistry (Harris, et al., 1992).
3. SX multi-airfoil segments with a generous grain defect specification are specified for low cost and enhanced turbine efficiency.

MECHANICAL PROPERTIES

Stress-rupture properties of SX CM 186 LC have been investigated as-cast and approximately 50% partial solutioned, both followed by 4 hrs/1975° F (1080°C) AC pseudo-coating diffusion heat treatment + 20 hrs/1600°F (871°C) AC final age (DA). Figure 2 shows a comparison of stress-rupture properties at 1742°F (950°C), 1800°F (982°C), 1900°F (1040°C) and 2000°F (1093°C) of approximately 50% partial solutioned SX CM 186 LC vs DS longitudinal CM 186 LC as-cast plus DA in both cases. There is an improvement in the SX stress-rupture strength vs DS, some of which is attributable to the approximately 50% partial γ′ solutioning. Comparative log stress vs log time to 1.0% creep, 2.0% creep and rupture data of SX CM 186 LC vs DS CM 247 LC® (longitudinal) (Harris, et al., 1984) are shown in Figs. 3, 4 and 5. DS CM 247 LC alloy has extensive vane segment turbine application experience.

Table 1. Nominal composition (wt. %) of CM 186 LC Superalloy.

C	Cr	Co	Mo	W	Ta	Re	Al	Ti	B	Zr	Hf	Ni	Density kg.dm^{-3}
0.07	6	9	0.5	8	3	3	5.7	0.7	0.015	0.005	1.4	Bal.	8.70

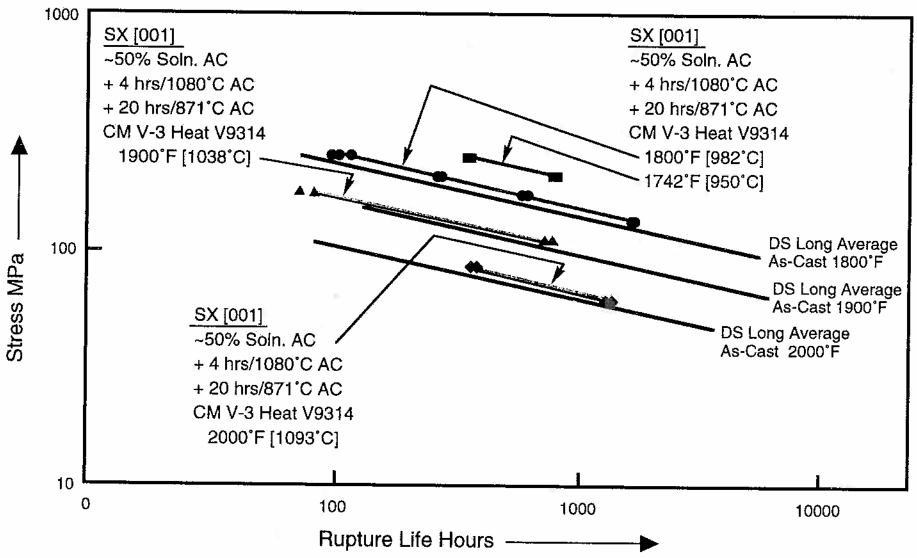

Figure 2. **Stress-Rupture**
SX CM 186 LC vs
DS CM 186 LC

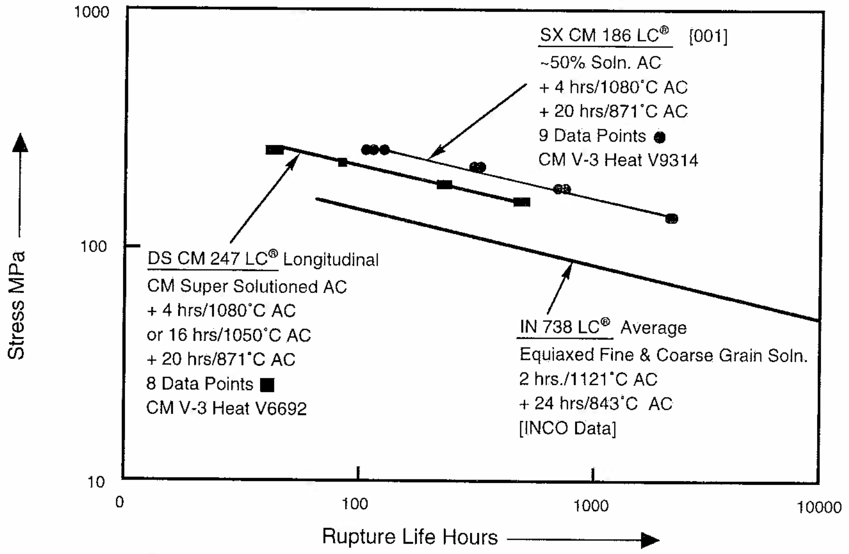

Figure 3. **Stress-Rupture**
1800°F (982°C)

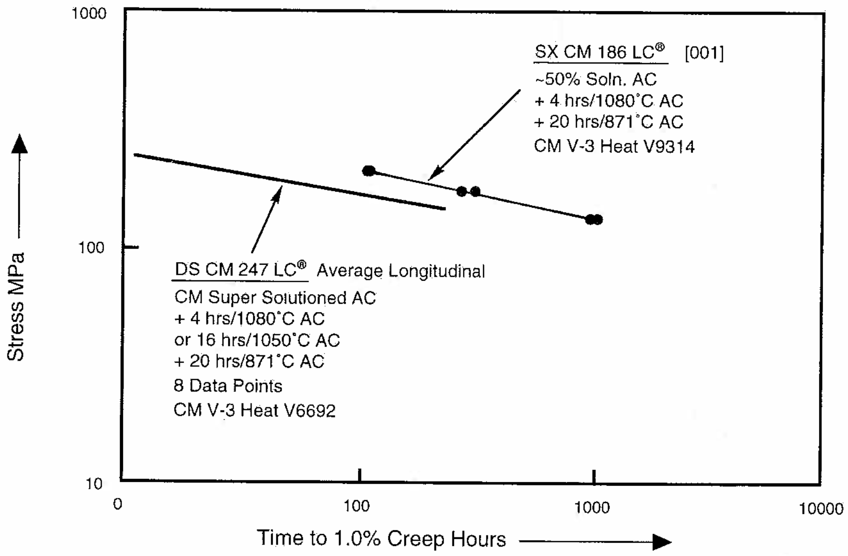

Figure 4. **Stress - 1.0% Creep**
1800°F (982°C)

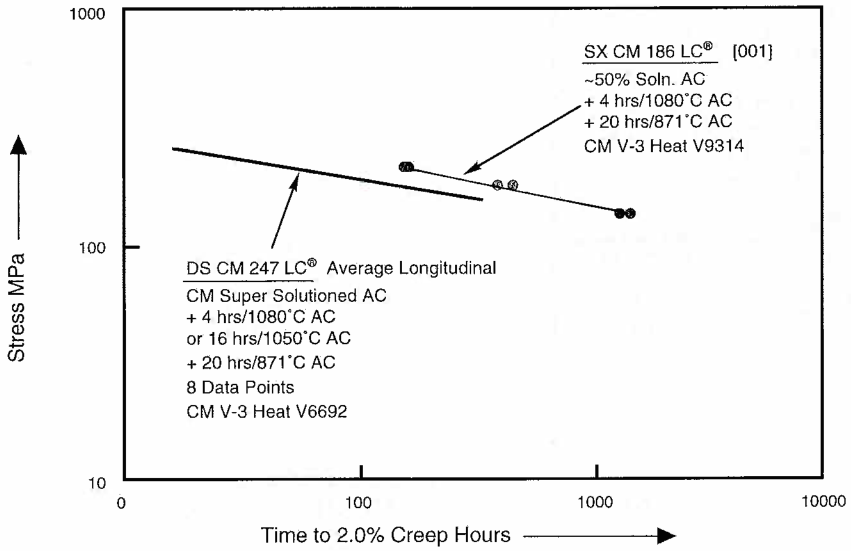

Figure 5. Stress - 2.0% Creep 1800°F (982°C)

Bicrystalline slabs were cast using, "seeding" techniques to evaluate the mechanical properties of SX CM 186 LC across high angle grain boundaries (HABs). Figure 6 shows the stress-rupture life retention at 1800°F (982°C) of SX CM 186 LC versus grain boundary misorientation angle. The 1800°F (982°C) test condition was selected because of the expected engine operating conditions. Also included are René N4 and René N data (Ross et al., 1996) which represent conventional SX alloy capability with and without deliberate additions of grain boundary strengthening elements (carbon and boron) respectively. The René N (without C & B) properties rapidly deteriorate with low angle boundaries (LABs) around 8-10°, whereas the carbon and boron grain boundary strengtheners in René N4 delay the dramatic drop-off to 15-20° HABs. In contrast the SX CM 186 LC optimised grain boundary strengtheners (C, B, Hf and Zr) [ie. the DS columnar grain chemistry] maintain the stress-rupture life properties at 1800°F (982°C) at approaching 100% of baseline value at grain boundary misorientation angles up to 35°, with significant life retention at HABs somewhat greater than 45°. The approximately 50% partial solutioning did not have a detrimental influence on rupture life across the grain boundaries.

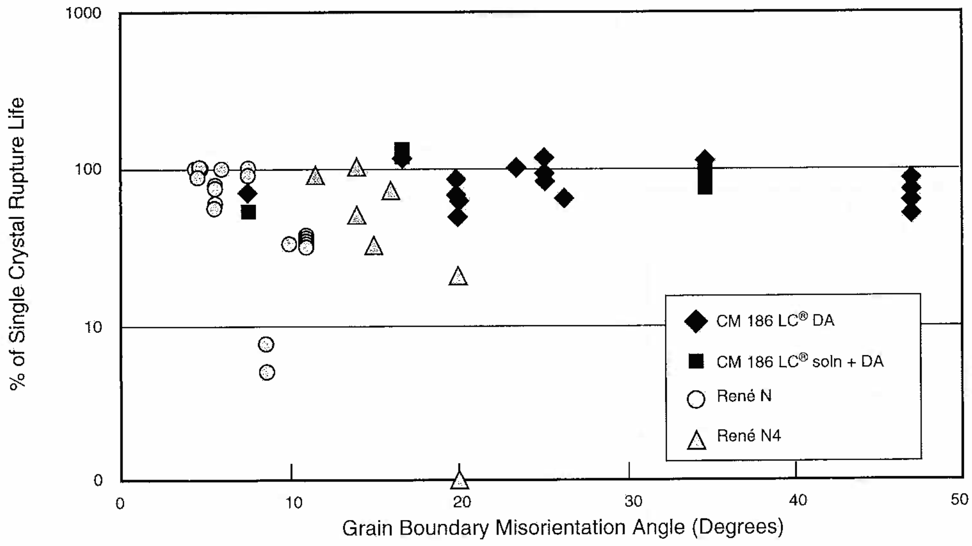

Figure 6. SX CM 186 LC Tolerance to Grain Boundary Misorientation (1800°F (982°C) Stress Rupture).

Figures 7 and 8 show that the 1900°F (1040°C) load controlled low cycle fatigue (LCF) property retention is also excellent for SX CM 186 LC in the presence of high angle boundaries at least up to 25°. Of course, the LCF life of CMSX-4® (Broomfield et al., 1998) is severely degraded by high angle boundaries ≥10°.

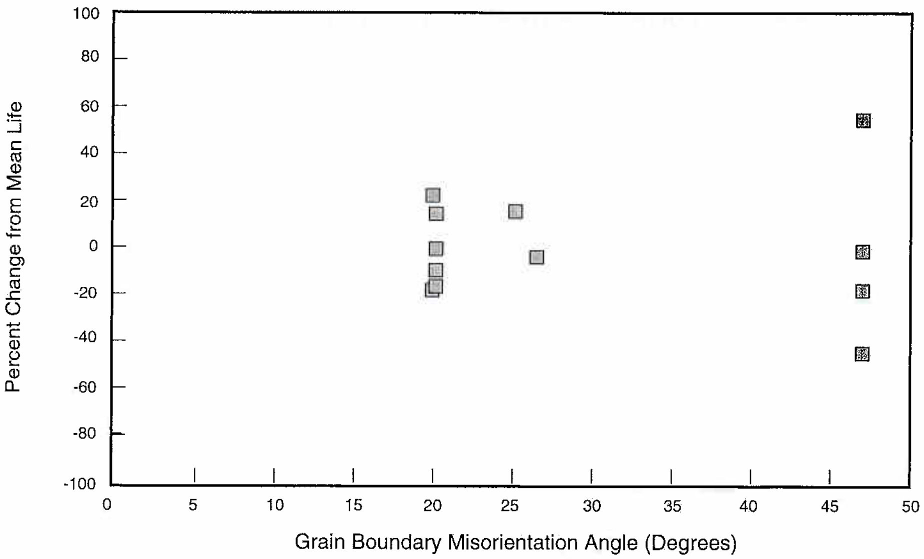

Figure 7. SX CM 186 LC Tolerance to Grain Boundary Misorientation (Low Cycle Fatigue - Load Controlled). [1900°F (1040°C)].

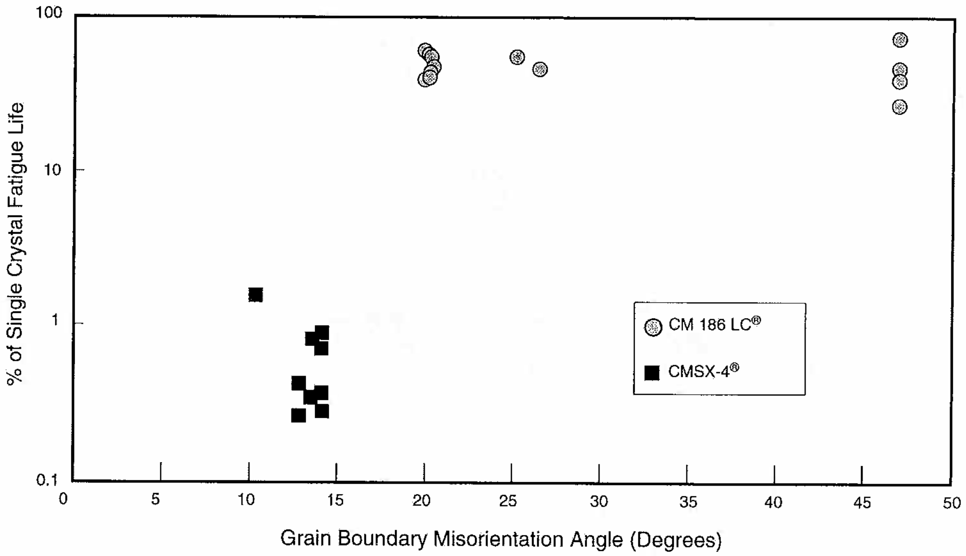

Figure 8. SX CM 186 LC vs CMSX-4 Tolerance to Grain Boundary Misorientation (Low Cycle Fatigue - Load Controlled) [1900°F (1040°C)].

OXIDATION AND HOT CORROSION

DS columnar grain CM 186 LC has been extensively burner rig tested for bare and coated oxidation and hot corrosion (sulfidation) (Korinko et al., 1996) as shown in Figs. 9, 10 and 11..

Improvements to the bare oxidation resistance of DS René 142 with small residual ppms of yttrium (Y) are shown in Fig. 12 (Ross et al., 1992). It would be expected that DS or SX CM 186 LC will show similar improved bare oxidation resistance with small residual ppms of lanthanum (La) and yttrium (Y) (Harris et al., 1991) and (Ford et al., 1998).

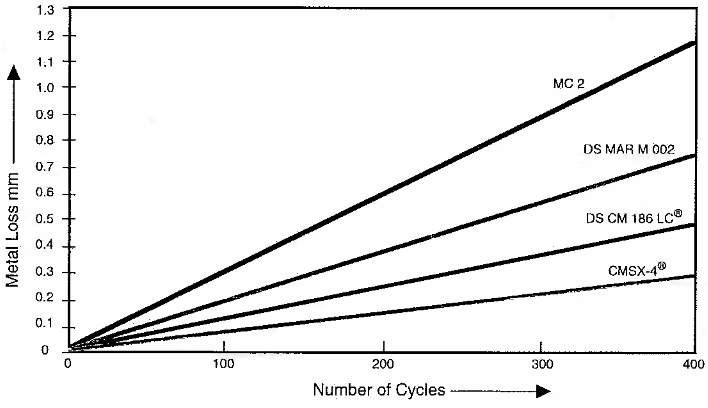

Figure 9. Burner Rig Cyclic Bare Oxidation, 2012°F (1100°C) 15 min. cycles 0.25 PPM NaCl. Mach 0.7 [Average Data]. [Courtesy RR].

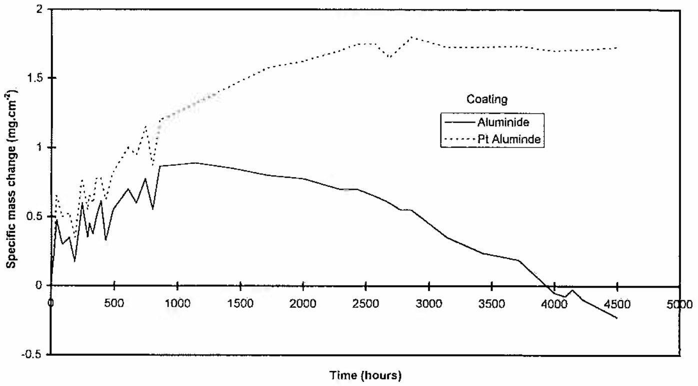

Figure 10. Burner Rig Dynamic Cyclic Oxidation of Coated DS CM 186 LC.
1900°F (1038°C) Mach 0.45. JP-5 Fuel. Cyclic once per hour. [RRA data].

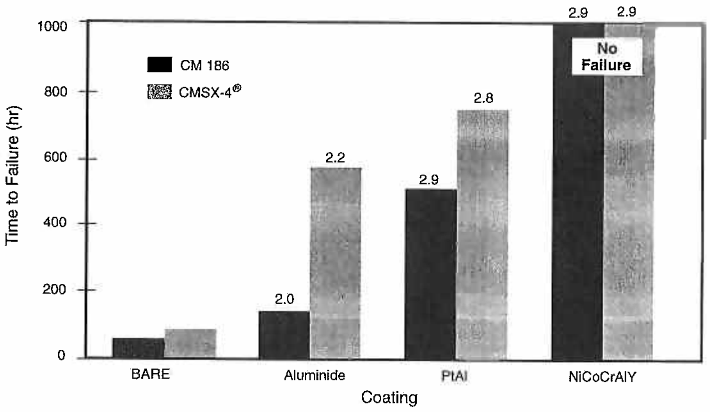

Figure 11. Accelerated Hot Corrosion Test
1650°F (899°C), 1% S in Fuel, 10 ppm Salt
LIfe of bare and coated CMSX-4 and CM 186 LC in Type 1 hot corrosion testing. [RRA data].

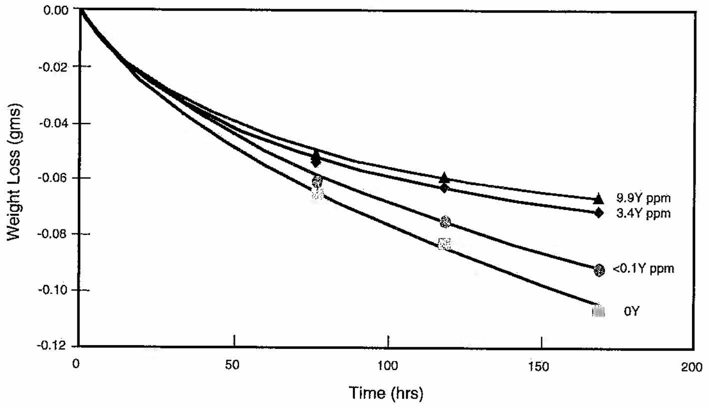

Figure 12. 2150°F (1177°C) Mach 1.0 oxidation test results showing the influence of yttrium additions to René 142 in retarding oxidation attack. (Ross, et al., 1992).

TURBINE ENGINE APPLICATION

The baseline equiaxed vane segment used in a RRA turbofan engine was air cooled IN 738 C alloy with a simple aluminide coating. While the configuration has performed acceptably in the baseline engine application, a recent recertification effort raised the turbine entry temperature by 165°F (92 °C) to provide an extended flat rating for the turbofan from ISA+15°C to ISA+30°C. This increase in temperature necessitated a more advanced material and SX CM 186 LC was selected for test and evaluation following the success with the initial SX casting trials and the grain boundary properties demonstrated for the alloy.

Significant turbine and manufacturing experience engine testing have show the SX CM 186 LC vanes offer excellent durability, creep and LCF strength combined with greatly improved casting yields. In an effort to obtain a cost effective SX vane segment alloy, it was recognized that SX CM 186 LC could tolerate high angle grain boundaries and other grain defects otherwise unacceptable to single crystal alloys. After the casting process was established at RRA [SCFO], nearly 100% of all castings were accepted through crystal verification with complete documentation of the noted grain structure. Engine testing was planned to assist in defining the upper limits of acceptability. However, after adopting these generous HAB acceptance limits and running extensive engine testing there has been absolutely no vane distress. Testing has included three 150 hour block tests on the A1/1, A1/2, and A1 engines (each model represents an increase in turbine inlet temperature). In each case 100% of the vane segments passed post-test fluorescent penetrant inspection with no defect indications apparent. Figures 13 and 14 show a representative SX vane segment after engine testing. This is a marked improvement over the baseline equiaxed vane operating at lower temperatures. In addition, an accelerated mission engine test has completed over 3000 cycles and the SX CM 186 LC vanes continue to perform without airfoil creep bowing or LCF initiated cracking in the airfoils or shrouds.

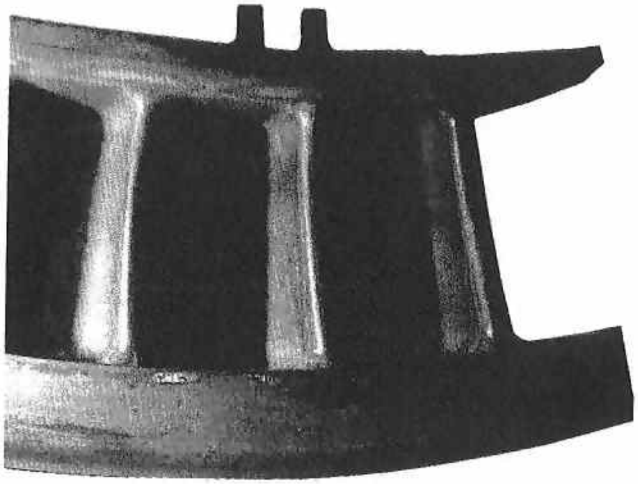

Figure 13. Leading Edge View of SX CM 186 LC Multiple Vane Segment After Completion of 150 hour FAA Engine Test.

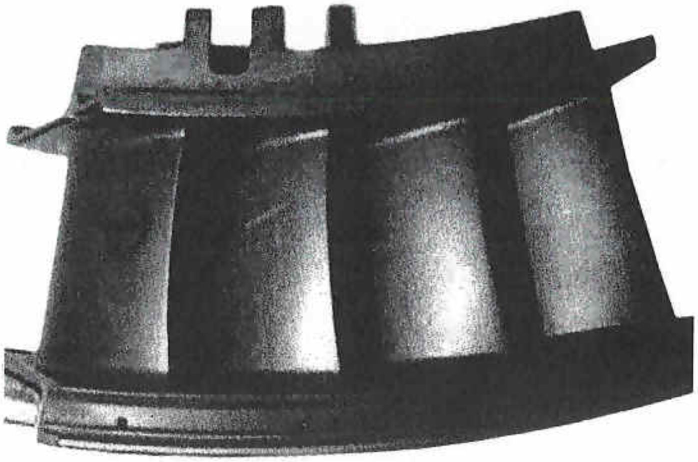

Figure 14. Trailing Edge View of SX CM 186 LC Multiple Vane Segment After Completion of 150 hour FAA Engine Test.

A supplementary benefit of using an existing established chemistry alloy was that coating and oxidation work did not require additional development funding; existing databases for DS CM 186 LC have been applied for SX CM 186 LC. Current RRA engines are using the SX CM 186 LC vanes with simple aluminide coatings, but platinum aluminide can be added at any time with the oxidation benefits already quantified.

CONCLUSIONS

A mutually developed SX vane segment application has been developed in a high strength DS superalloy, CM 186 LC, for a RRA turbofan application to FAA certification in less than two years from initial SX castability trials.

Accelerated mission turbine engine testing has been completed to over 3000 cycles with the low cost SX vanes in CM 186 LC continuing to perform without problems.

The SX castability of the alloy has also exceeded expectations, which along with the generous grain specifications with resultant high casting yield and absence of a vacuum solution heat treatment and Rx, result in appreciably lower manufacturing costs.

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