NEW SUPERALLOY CONCEPTS FOR SINGLE CRYSTAL TURBINE VANES AND BLADES

Ken Harris, Jacqueline B. Wahl
Cannon-Muskegon Corporation
[SPS Technologies, Inc.]
[Muskegon, Michigan, USA]

ABSTRACT
Integrated superalloy/component design/manufacturing technology utilizing 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 utilizing 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.

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, manufacturing cost can be prohibitive due to low casting and solution heat treatment yields due to rejectable grain defects. Ultra high creep and fatigue strength SX alloys are limited to low angle boundaries (LABs) normally not exceeding 6° in critical airfoil locations. Aero engine vane segment and large single vanes for industrial gas turbines (IGTs) can result in not only LAB defects exceeding 9° - 12° but also high angle grain boundary (HAB) defects ≥ 15°, along with recrystallized grains occurring during solution heat treatment.

CM 186 LC® is a hafnium (Hf) containing nickel-base superalloy developed for directionally solidified (DS) columnar grain turbine airfoils. It 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 carbon (C), boron (B), Hf and zirconium (Zr) and consequent carbide and boride grain boundary phases to give good combination of transverse mechanical properties in DS columnar grain turbine airfoils. CM 186 LC has excellent DS castability, oxidation and coating performance and is used as-cast with attractive longitudinal creep and low cycle fatigue (LCF) properties. SX casting experience - development and production - has shown the alloy can be readily cast into aero engine vanes and vane segments. Mechanical property, turbine engine testing and flight engine service experience show the alloy

Presented at PARSONS 2000, 5th International Charles Parsons Turbine Conference, 3 - 7 July 2000, Churchill College, Cambridge, UK

can accommodate grain boundaries at least up to 25° resulting in high casting yields. These SX vane components are either used as-cast or approximately 50% partial solutioned which avoid any recrystallization (Rx) problems. Component costs can be < 50% of that of a conventional high purity SX alloy.

INTRODUCTION

There is a recognized need in both the aerospace and power generation gas turbine industry for advanced technology materials at reduced costs. The benefit of single crystal cast components has been well documented: aero turbine engine testing and service experience have demonstrated the enhanced service life of SX vane segments compared to their equiaxed, polycrystalline counterparts (Burkholder et al (1)). This improvement is a result of the superior thermal fatigue, LCF, creep strength, oxidation and coating performance of SX superalloys and the absence of grain boundaries in SX vane segments. SX alloys also demonstrate a significant improvement in thin wall (cooled airfoil) creep properties compared to polycrystalline superalloys (Fig. 1). However, SX components require tight limits on tolerance for grain defects such as low angle boundaries and solution heat treatment-induced recrystallized grains, which reduce yield and, as a result, increase manufacturing costs.

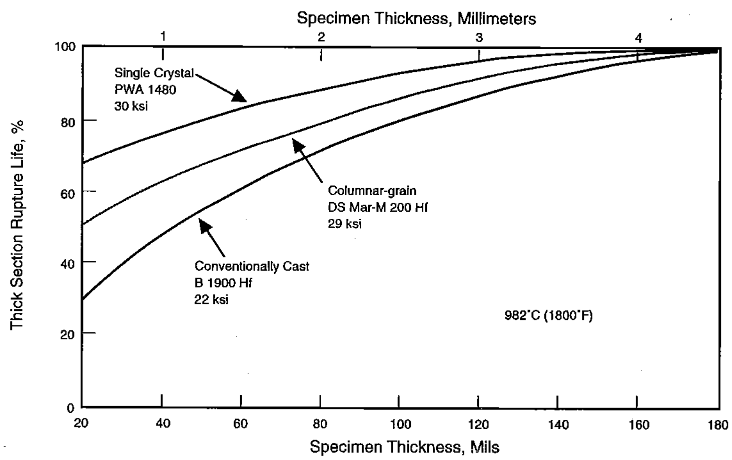

Figure 1. Single Crystal Superalloys retain a higher fraction of their thick section rupture life at thin sections below 150 mils. (.150") (3.8 mm) than polycrystalline superalloys. [Courtesy PWA]

Directionally solidified castings of Re-bearing columnar grain nickel base superalloys have successfully been used to replace first generation (non Re-bearing) single crystal alloys at a cost savings due to higher casting yields (Cetel et al (2)). However, DS components are less advantageous than SX vanes due to grain boundaries in non-airfoil regions, particularly the inner and outer shrouds of multiple airfoil segments exhibiting high, complex stress conditions. 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. 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. Clearly, what is needed is the benefits of SX casting technology combined with an increased tolerance for grain defects to improve casting yield and reduce component cost.

To address this need, the concept to use CM 186 LC (Caruel et al (3)) SX vane segments was mutually developed and designed into the latest versions of the Rolls-Royce Allison (RRA) turbofan engines. The approach evaluated included:

1. "Seeded" SX casting technology to produce SX vane segments
2. A high creep strength, ductile, Re-containing DS superalloy (CM 186 LC), with no changes to alloy chemistry (Harris et al (4))
3. SX multi-airfoil segments with a generous grain defect specification for low cost and improved turbine efficiency

ALLOY SELECTION

CM 186 LC (Table I) is a 3% Re-bearing, highly alloyed nickel-base superalloy developed for DS columnar grain turbine airfoils with demonstrated favorable turbine engine service experience (McColvin et al (5)). CM 186 LC contains optimum amounts of C, B, Hf and Zr, which result in carbide and boride grain boundary strengthening phases and provide good transverse creep-rupture strength, ductility and LCF properties in DS columnar grain turbine airfoils. These same strengthening phases are beneficial in the SX cast components to strengthen LAB/HAB grain defects allowing more generous grain acceptance criteria and improving casting yield.

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

Table 1. Nominal compositon (wt. %) for CM 186 LC Superalloy.

Development and production SX casting experience with CM 186 LC demonstrate the alloy can be readily cast into aero turbine multi-airfoil segments. These SX vane components are either used as-cast or approximately 50% partial solutioned. Partial solutioning imparts a benefit to short term stress-rupture life; however, there is no benefit to long term rupture lives. The absence of a high temperature solutioning cycle avoids any recrystallization problems and minimizes post-cast processing operations, thereby reducing component cost.

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. Typical microstructure following partial solutioning plus a double age is shown in Figure 2. A comparison of longitudinal stress-rupture properties of approximately 50% partial solutioned SX CM 186 LC vs DS CM 186 LC as-cast at 1742°F (950°C), 1800°F (982°C), 1900°F (1040°C) and 2000°F (1093°C) is shown in

Figure 3. 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) at 1800°F (982°C) (Harris et al (6)) are shown in Figures 4 - 6. DS CM 247 LC alloy has extensive vane segment turbine application experience.

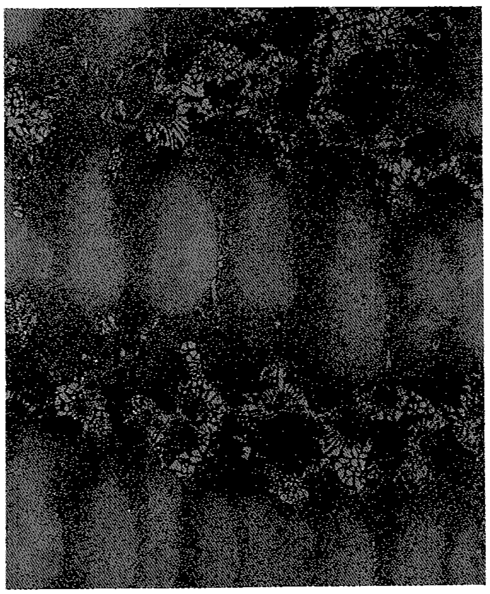

Figure 2. Typical Microstructure of SX CM 186 LC following ~50% Soln. AC + Double Age

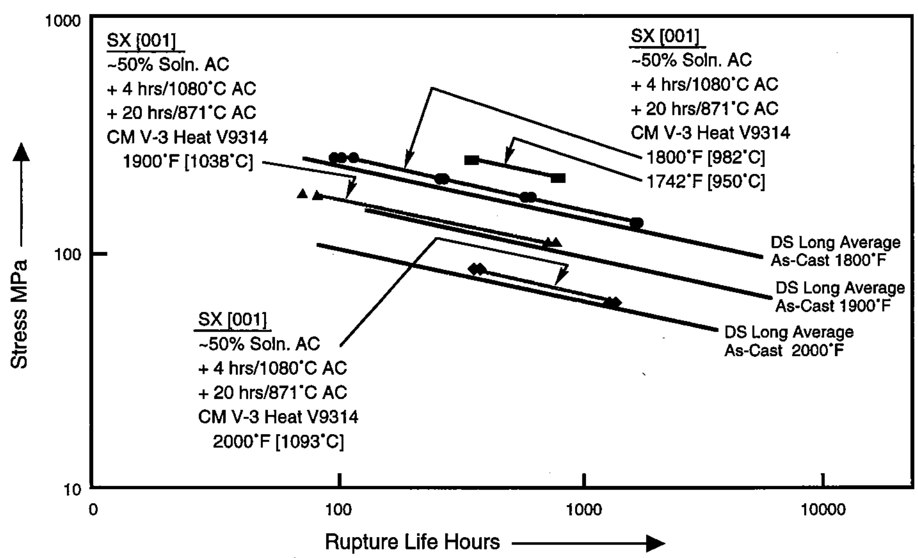

Figure 3. <u>Stress-Rupture</u> SX CM 186 LC vs DS CM 186 LC

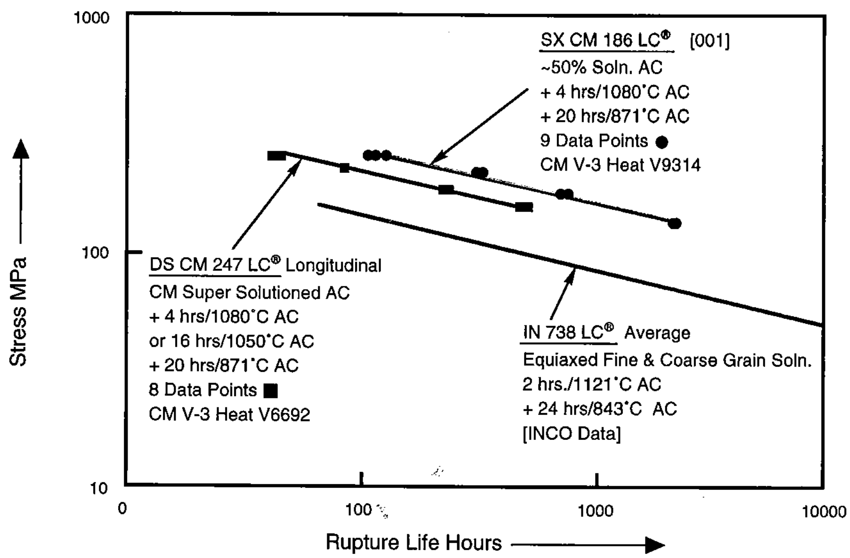

Figure 4. <u>Stress-Rupture</u> 1800°F (982°C)

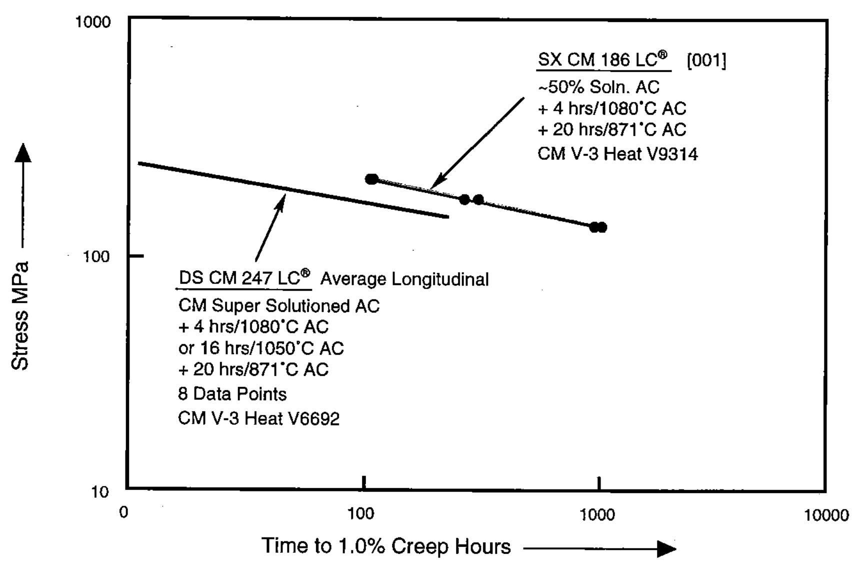

Figure 5. <u>Stress - 1.0% Creep</u> 1800°F (982°C)

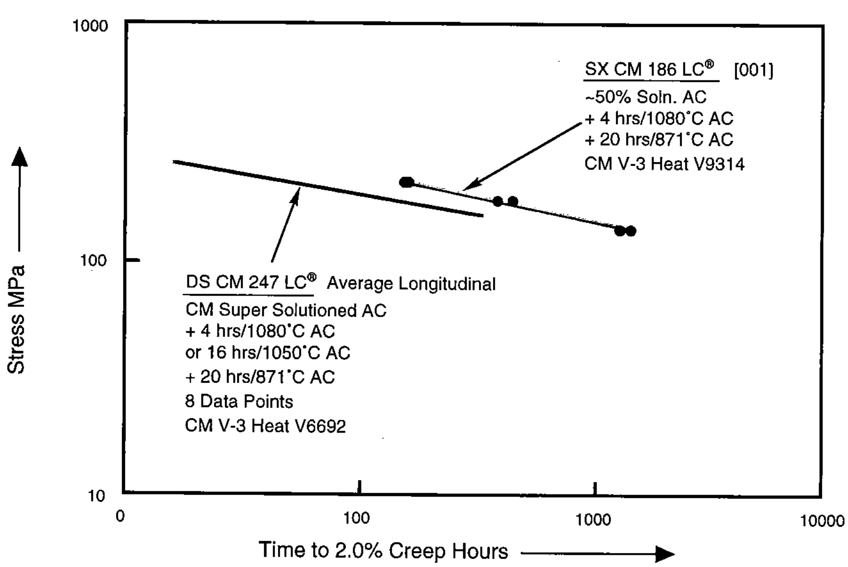

Figure 6.
<u>Stress - 2.0% Creep</u>
1800°F (982°C)

High purity (carbon and boron free), ultra high creep and fatigue strength SX alloys are limited to LABs normally not exceeding 6° in critical airfoil locations. Carbon and boron containing SX superalloys can accommodate low angle boundaries in the 9° - 12° range but with a resultant overall sacrifice in creep and fatigue properties. Aero engine vane segment and large single vanes for IGT engines with complex configurations can result in LAB defects exceeding 9° - 12°, along with high angle grain boundary defects ≥ 15° occurring during the SX solidification process. This can be further exacerbated by recrystallized grains occurring during solution heat treatment from residual casting stresses and associated strain.

Bicrystalline slabs were cast using "seeding" techniques to evaluate the mechanical properties of SX CM 186 LC across LAB/HAB grain defects. The stress-rupture life retention at 1800°F (982°C) of SX CM 186 LC versus grain boundary misorientation angle is shown in Figure 7. Also included are René N4 and René N data (Ross et al (7)) 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 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 optimized grain boundary strengtheners (C, B, Hf and Zr) maintain stress-rupture life at 1800°F (982°C) 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.

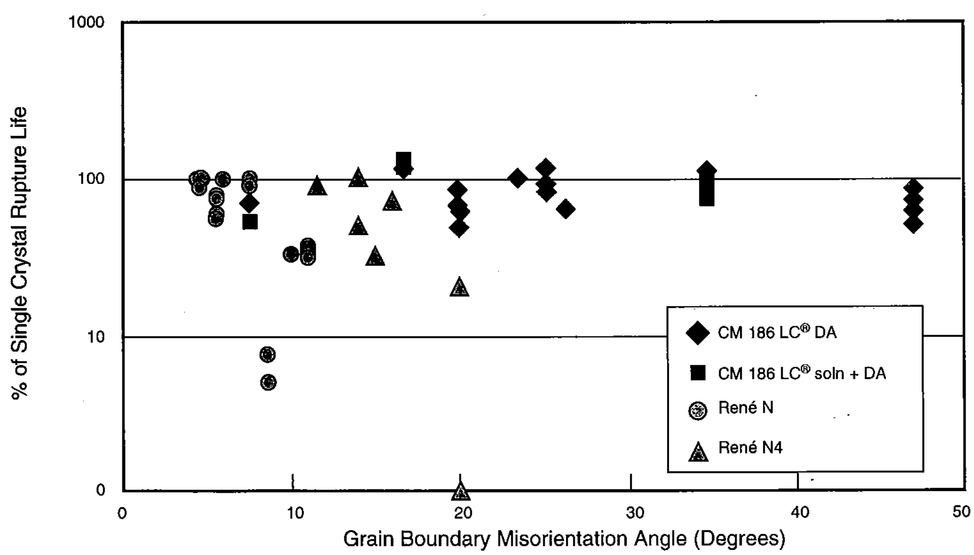

Figure 7. SX CM 186 LC Tolerance to Grain Boundary Misorientation (1800°F (982°C) Stress Rupture).

Similar retention of rupture life was found for LABs/HABs exceeding 20° at 1742°F (950°C), 1800°F (982°C), 1900°F (1040°C) and 2000°F (1093°C) (Fig. 8). SX CM 186 LC also exhibited excellent transverse ductility which precludes fatigue cracking inherent in other vane segment alloys. The ductility is visually demonstrated in the microstructure of post creep-rupture specimens (Fig. 9).

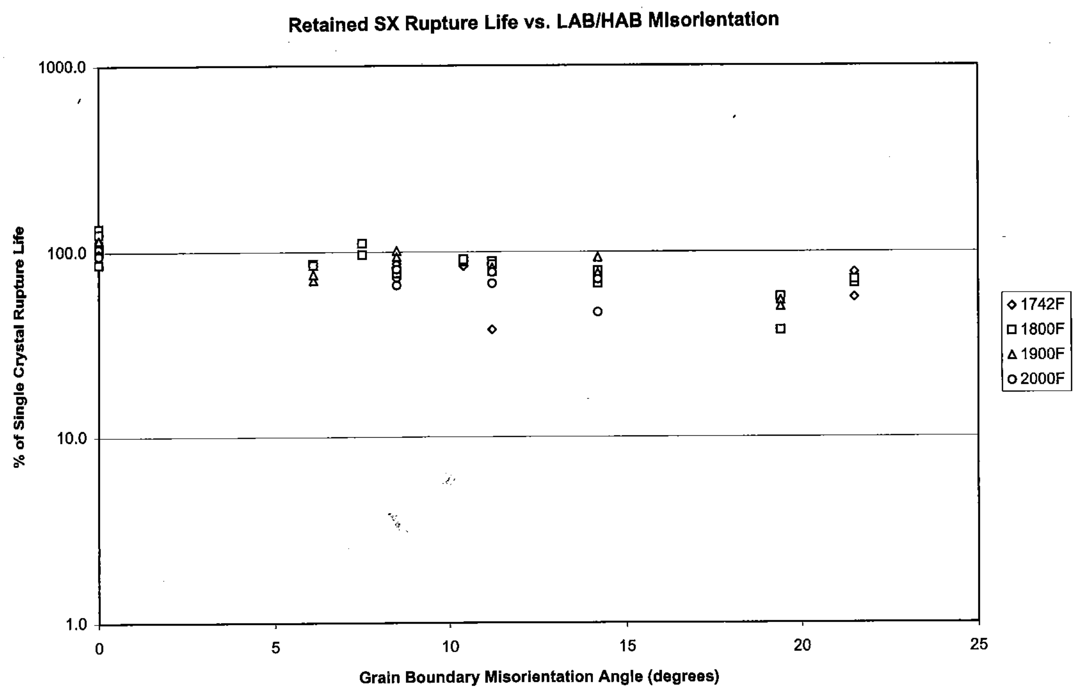

Figure 8. SX CM 186 LC Tolerance to Grain Boundary Misorientation

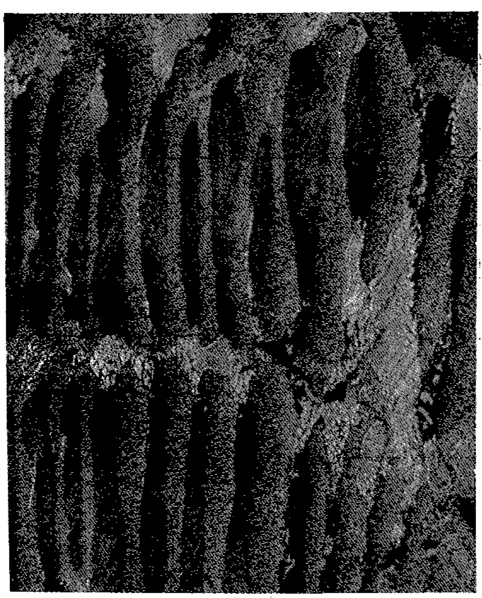

Figure 9. Typical Microstructure of SX CM 186 LC near the Fracture Following Transverse Creep-Rupture Testing

Low cycle fatigue life at 1900°F (1040°C) exhibited excellent retention of properties across HABs (Figs. 10 and 11). In comparison, the LCF life of CMSX-4® (Broomfield et al (8)) is severely degraded by high angle boundaries ≥10° due to the lack of grain boundary strengthening additions.

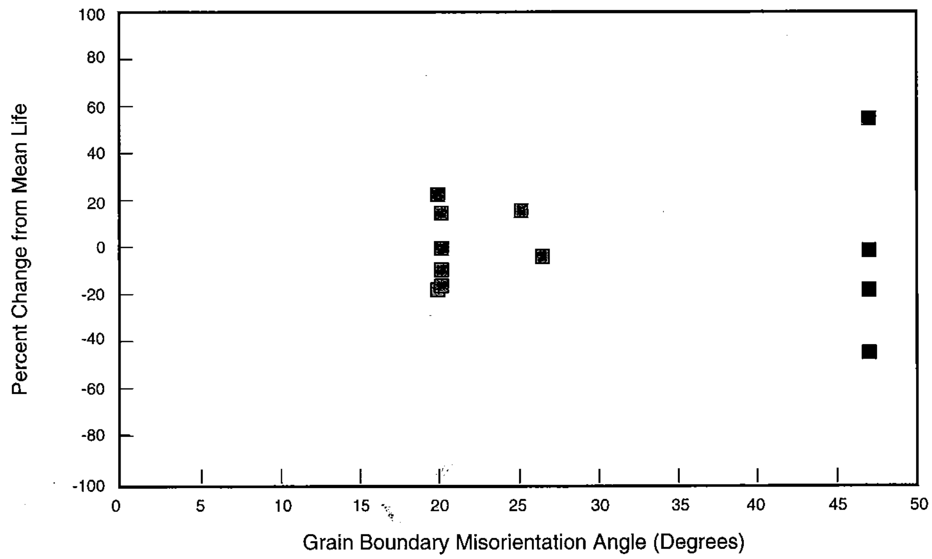

Figure 10. SX CM 186 Tolerance to Grain Boundary Misorientation (Low Cycle Fatigue - Load Controlled).

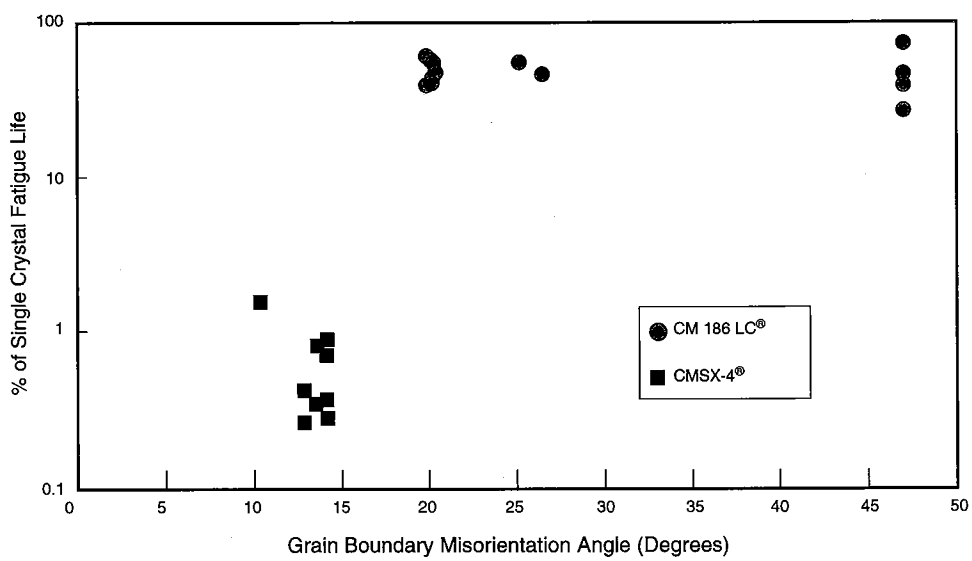

Figure 11. SX CM 186 LC Tolerance to Grain Boundary Misorientation (Low Cycle Fatigue - Load Controlled) [1900°F (1040°C]

The LAB/HAB property results validate the concept of combining SX casting technology with a DS alloy composition to provide attractive mechanical properties with the advantages of SX structure and DS strengthening of any grain defects. This should allow increased accommodation for grain defects, increase the casting yield and reduce the per piece component cost.

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 (9)) as shown in Figures 12 - 14. It is expected SX CM 186 LC will show comparable performance. Improvements to bare oxidation resistance of DS René 142 with small residual ppm of yttrium (Y) are shown in Figure 15 (Ross et al (10)). It would be expected that DS or SX CM 186 LC will also show improved bare oxidation resistance with small residual ppms of lanthanum (La) and yttrium (Harris et al (11)) and (Ford et al (12)).

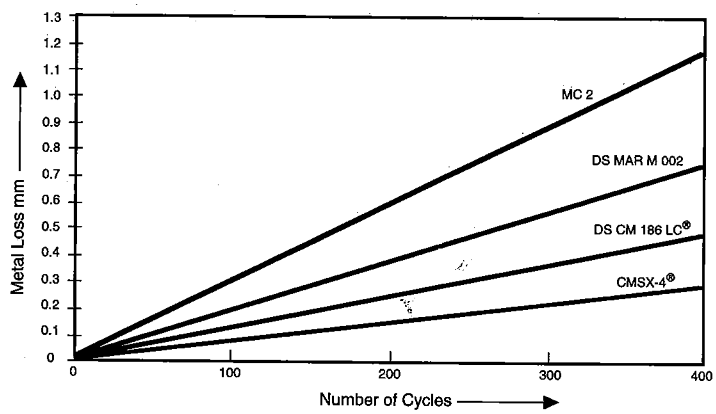

Figure 12. Burner Rig Cyclic Bare Oxidation, 2012°F (1100°C) 15 min. cycles 0.25 PPM NaCl. Mach 0.7 0.7 [Average Data]. [Courtesy RR].

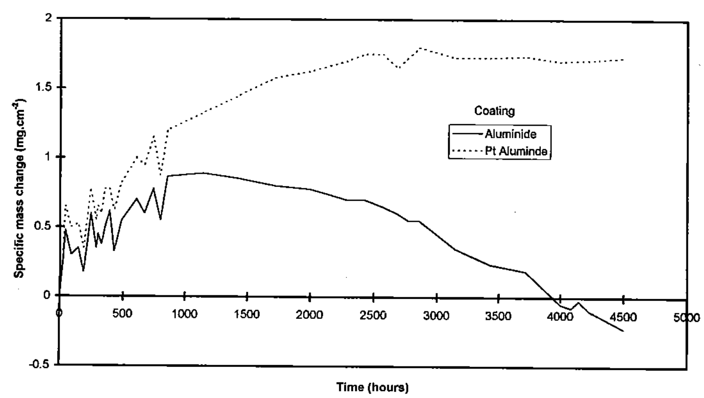

Figure 13. Burner Rig Dynamic Cyclic Oxidation of Coated DS CM 186 LC. 1900°F (1038°C) Mach 0.45. JP-5 Fuel. Cyclic once per hour. [RRA Data]

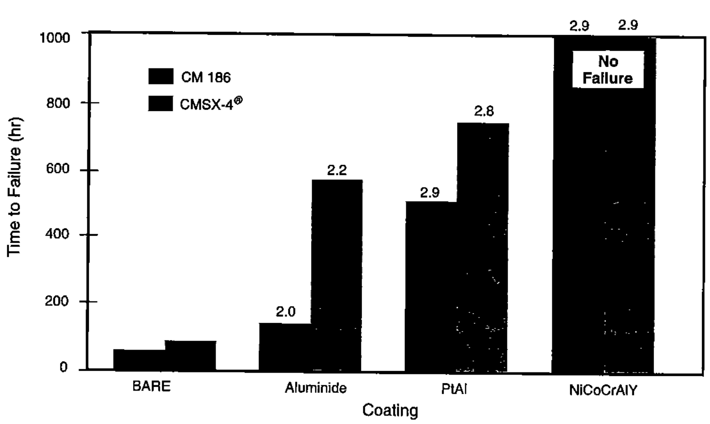

Figure 14. Accelerated Hot Corrosion Test 1650°F (899°C), 1% S in Fuel, 10 ppm Salt Life of bare and coated CMSX-4 and CM 186 LC in Type 1 hot corrosion testing. [RRA data].

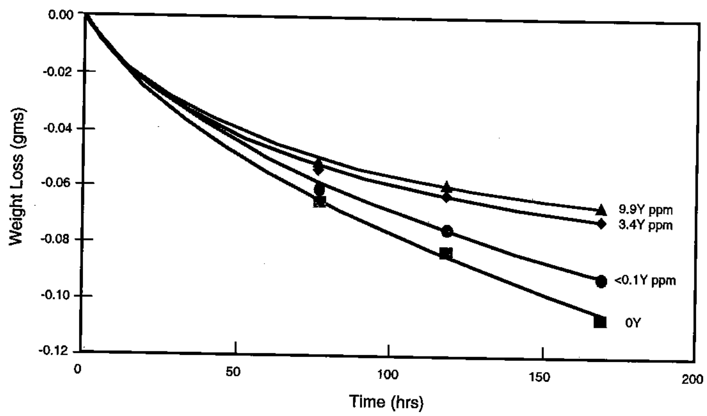

Figure 15. 2150° (1177°C) Mach 1.0 oxidation test results showing the influence of yttrium additions to René 142 in retarding oxidation attack (Ross et al (10)).

TURBINE ENGINE APPLICATION

The baseline equiaxed vane segment used in a RRA turbofan engine was an 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.

Significant engine testing has show the SX CM 186 LC offers excellent durability and strength with greatly improved casting yields. In an effort to obtain a cost effective 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 and fixed, 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 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 (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 indications. This is a marked improvement over the baseline equiaxed vane operating at lower temperatures.

In addition, an accelerated mission engine test has completed nearly 3000 cycles and the SX CM 186 LC vanes continue to perform above original expectations. Representative photos after 2260 hours/2936 cycles (Figs. 16 and 17) show no evidence of trailing edge bowing due to creep, thermo-mechanical or thermal fatigue cracking. Although some leading edge coating degradation is evident, this casting was coated with a simple aluminide coating. A supplementary benefit of using an existing chemistry alloy was that coating and oxidation work did not require additional development funding; existing databases for DS CM 186 LC also apply for SX CM 186 LC. Current RRA turbofans 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.

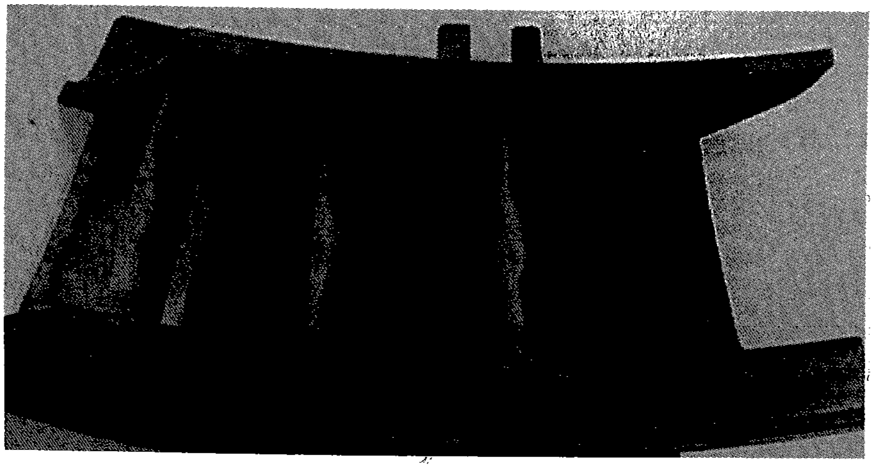

Figure 16. Leading Edge View of SX CM 186 LC Multiple Vane Segment After Completion of 2660 hours/2936 cycles Engine Bench Test.

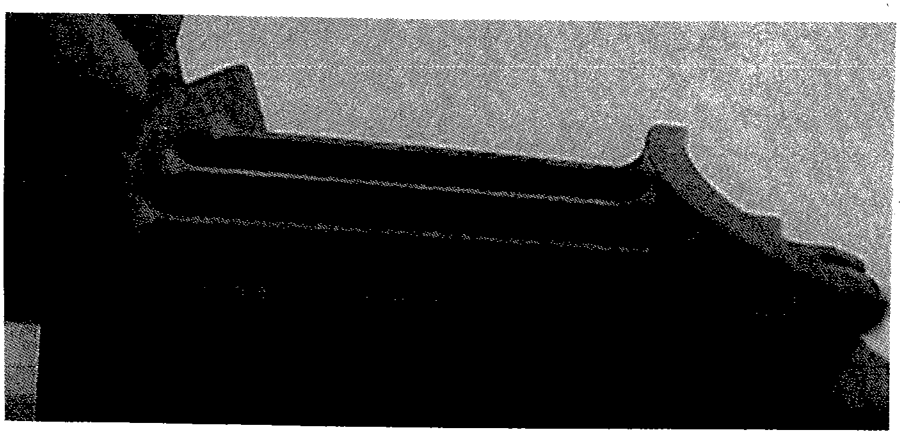

Figure 17. Trailing Edge View of SX CM 186 LC Multiple Vane Segment After Completion of 2660 hours/2936 cycles Engine Bench Test.

CONCLUSIONS

A mutually developed SX vane segment application has been demonstrated utilizing a high strength DS superalloy, CM 186 LC, for a RRA turbofan flight engine application. Mechanical property, casting trial and test and flight engine experience have confirmed the validity of this new concept to SX cast a DS Re-bearing superalloy into a high yield, low cost component for aero and IGT applications. This has culminated in FAA certification of this component in less than two years from initial SX castability trials.

Accelerated mission turbine engine testing has been completed to nearly 3000 cycles with the low cost SX vanes in CM 186 LC continuing to perform above original expectations. The SX castability of the alloy has also exceeded expectations and combined with generous grain specifications has produced a high yield casting process. Since CM 186 LC requires no solution heat treatment, RX concerns have been eliminated and post-cast processing is simplified. This combination of features has produced an attractive low cost manufacturing process.

REFERENCES

1. Burkholder P.S., Thomas M.C., Frasier D.J. and Whetstone J.R. (Allison) Harris K., Erickson G.L., Sikkenga S.L. and Eridon J.M. (CM), April 25-27, 1995, "Allison Engine

Testing CMSX-4® Single Crystal Turbine Blades and Vanes," *IOM 3rd International Charles Parsons Turb. Conf. Proc.*, Newcastle upon Tyne, UK.
2. Cetel A.D. and Duhl D.N. (PWA), Sept. 1992, "Second Generation Columnar Grain Nickel-Base Superalloy," *7th International Symposium Proc.,* Seven Spring, Champion PA, USA, *Superalloys 1992*, edited by Antolovich S.E. et al., ed., The Minerals, Metals & Materials Society. pp 287-296.
3. Caruel F., Bourguignon S., Lallement B., Fargeas S. And DeBussac A. (SNECMA), Harris K., Erickson G.L. and Wahl J.B. (CM), January 1998, "SNECMA Experience with Cost-Effective DS Airfoil Technology Applied Using CM 186 LC Alloy," *ASME Journal of Engineering for Gas Turbines and Power*, Vol. 120, pps 97-104.
4. Harris K., Erickson G.L. and Sikkenga S.L. (CM), Brentnall W.D., Aurrecoechea J.M. and Kubarych K.G. (Solar®) 20-24 September 1992, "Development of the Rhenium Containing Superalloys CMSX-4 & CM 186 LC for Single Crystal Blade and Directionally Solidified Vane Applications in Advanced Turbine Engines," *The Metallurgical Society of AIME, 7th International Symposium on Superalloys*, Seven Springs, Champion, Pennsylvania, USA.
5. McColvin M. and Sutton J. (EGT), Whitehurst M., (GEC Alsthom), Fleck D.G. and VanVranken T. A. (PCC), Harris K., Erickson G.L. and Wahl J.B. (CM) November 4-6, 1997, "Application of the Second Generation DS Superalloy CM 186 LC® to First Stage Turbine Blading in EGT Industrial Gas Turbines," *IOM 4th International Charles Parsons Turbine Conf. Proc.*, Newcastle upon Tyne, UK.
6. Harris K., Erickson G.L. and Schwer R.E. (CM) October 7-11, 1984, "MAR M 247 Derivation - CM 247 LC DS Alloy CMSX Single Crystal Alloys Properties & Performance," *The Metallurgical Society of AIME, 5th International Symposium on Superalloys Proc.*, Seven Springs, Champion, Pennsylvania, USA
7. Ross E.W. and O'Hara K.S. (GE) 1996, "René N4: A First Generation Single Crystal Turbine Airfoil Alloy with Improved Oxidation Resistance, Low Angle Boundary Strength and Superior Long Time Rupture Strength," *Superalloys 1996*, edited by Kissinger R.D. et al., ed,, The Minerals, Metals & Materials Society.
8. Broomfield R.W., Ford D.A. and Bhangu J.K. (RR plc), Thomas M.C., Frasier D.J. and Burkholder P.S. (RR Allison), Harris K., Erickson G.L. and Wahl J.B. (CM), July 1998, "Development and Turbine Engine Performance of Three Advanced Rhenium Containing Superalloys for Single Crystal and Directionally Solidified Blades and Vanes," *ASME Journal of Engineering for Gas Turbines and Power*, Vol. 120, pps 595-608.
9. Korinko, P.S., Barber, M.J. and Thomas M. (RR Allison) June 10-13, 1996, "Coating Characterization and Evaluation of Directionally Solidified CM 186 LC® and Single Crystal CMSX-4®," *ASME "TURBO EXPO '96"*, NEC, Birmingham, UK.
10. Ross E.W. and O'Hara K.S. (GE) 1992, "René 142: A High Strength, Oxidation Resistant DS Turbine Airfoil Alloy," *Superalloys 1992*, edited by Antolevich S.D., et al., ed., The Minerals, Metals & Materials Society.
11. Harris K. and Erickson G.L., U.S. Patent #5,069,873 Low Carbon DS Alloy (CM 186 LC) 3 December 1991.
12. Ford D.A., Bhangu H.K. and Fullagar K.P.L. (Rolls-Royce), Thomas M.C., Korinko P.S. and Burkholder P.S. (RR Allison), Harris K. and Wahl J. (CM), 5-7 October 1998, "Improved Performance CMSX-4® Alloy Turbine Blades Utilising PPM Levels of Lanthanum and Yttrium," *6th Liège Conference, Materials for Advanced Power Engineering*, Liège, Belgium.