DEVELOPMENT OF THE RHENIUM CONTAINING SUPERALLOYS CMSX-4® & CM 186 LC® FOR SINGLE CRYSTAL BLADE AND DIRECTIONALLY SOLIDIFIED VANE APPLICATIONS IN ADVANCED TURBINE ENGINES

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Summary

A team approach involving several turbine engine companies utilizing the concepts of simultaneous engineering, has been used to successfully develop CMSX-4 alloy for turbine blade applications. The high level of balanced properties determined by laboratory evaluation, has been confirmed during field testing the Solar Mars T-14000 industrial gas turbine with CMSX-4 single crystal (SX) blades in both the coated and bare condition.

A similar collaborative approach has resulted in the successful development of CM 186 LC alloy for complex, directionally solidified (DS) columnar grain vane segments. Excellent component producibility and quality is demonstrated. Turbine engine testing is scheduled to commence by the end of the year.

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Introduction

Increased operating temperatures and higher rotational speeds resulting in increased component stresses, are primary goals in the continuing development of the gas turbine to provide improved fuel efficiency and power-to-weight performance. Cost reduction, from improvements in turbine component producibility and process yield, and through gains in airfoil component durability, is an additional objective.

The greatest advances in metal temperature and stress capability for turbine blades in the last 30 years has been the result of the development of single crystal superalloy, casting process and engine application technology pioneered by Pratt and Whitney Aircraft (1 thru 19 inclusive). The compositions of the first generation single crystal superalloys which have attained turbine engine application status are shown in Table I . These alloys are characterized by similar creep-rupture strength. However, they exhibit differing single crystal castability, residual gamma/gamma prime (γ/γ') eutectic phase content following solutioning, propensity for recrystallization during solution heat treatment, absence or presence of carbides, impact and mechanical fatigue properties (HCF & LCF), environmental oxidation and hot corrosion properties and density.

Carbon has been included in some single crystal alloy compositions to assist vacuum induction refining and alloy cleanliness. However, the carbide interfaces with the metal matrix are surfaces of high energy and can act as crack initiation sites along with fractured carbides during creep deformation and mechanical fatigue loading (20). Casting micropores in NON-HIP'ed single crystal castings can also be of prime importance in determining the mechanical fatigue life. Fatigue cracking initiates at the micropores and the crack initiation can occur quite early in notched specimens. It is reported that the micropores in a single crystal first generation alloy become coated with γ' during high temperature service exposure and fatigue cracks nucleate in the γ' coating the pore (21).

First Generation Single Crystal Superalloys

Alloy	Nominal Composition, wt. % Cr	Co	Mo	W	Ta	V	Cb (Nb)	Al	Ti	Hf	Ni	Density kg/dm³
PWA 1480 (1)	10	5	-	4	12	-	-	5.0	1.5	-	BAL	8.70
René N-4 (2,3)	9	8	2	6	4	-	.5	3.7	4.2	-	BAL	8.56
SRR 99 (5,6)	8	5	-	10	3	-	-	5.5	2.2	-	BAL	8.56
RR 2000 (5,6)	10	15	3	-	-	1	-	5.5	4.0	-	BAL	7.87
AM1 (8)	8	6	2	6	9	-	-	5.2	1.2	-	BAL	8.59
AM3 (19)	8	6	2	5	4	-	-	6.0	2.0	-	BAL	8.25
CMSX-2 (11,14)	8	5	.6	8	6	-	-	5.6	1.0	-	BAL	8.56
CMSX-3 (11,14)	8	5	.6	8	6	-	-	5.6	1.0	.1	BAL	8.56
CMSX-6® (15)	10	5	3	-	2	-	-	4.8	4.7	.1	BAL	7.98
AF 56 (7)	12	8	2	4	5	-	-	3.4	4.2	-	BAL	8.25

Table I

Second Generation Single Crystal Allovs

	Nominal Composition, wt. % Cr	Co	Mo	W	Ta	Re	Al	Ti	Hf	Ni	Density kg/dm³
CMSX-4 (23)	6.5	9	.6	6	6.5	3	5.6	1.0	.1	BAL	8.70
PWA 1484 (17)	5	10	2	6	9	3	5.6	-	.1	BAL	8.95
SC 180 (36)	5	10	2	5	8.5	3	5.2	1.0	.1	BAL	8.84
MC2 (24)	8	5	2	8	6	-	5.0	1.5	-	BAL	8.63

Table II

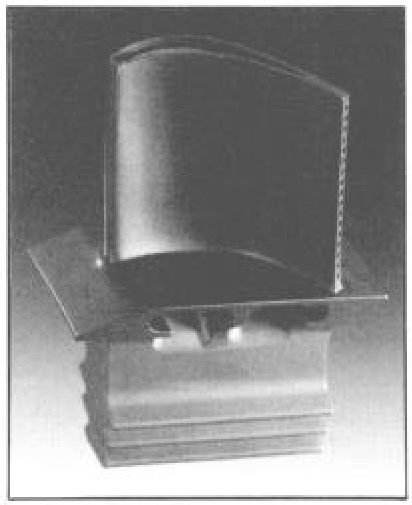
Turbine engine experience with the first generation single crystal alloys has resulted in process developments being combined with second generation alloy development, to improve and maximize overall properties of the turbine airfoil components (23). Microstructures can be optimized to be fully solutioned and HIP'ed, to contain neither γ/γ' eutectic phase, nor regions of incipient melting, carbides, nor microporosity (22). The published compositions of several second generation single crystal alloys are shown in Table II.

CMSX-2®, CMSX-3®, CMSX-4®, CMSX-6®, CM 247 LC® & CM 186 LC® are registered trademarks of the Cannon-Muskegon Corporation.

Allison has reported completion of initial turbine engine testing of a highly advanced, variable cycle core that offers the potential for doubling powerplant hot-section life and reducing high-pressure turbine weight by 30% (25). Eventually this IHPTET engine is targeted to double engine thrust-to-weight ratio from the best current (10:1) to 20:1, while cutting fuel consumption by 38%. The engine features a turbine wheel with blades fabricated from Lamilloy® single crystal materials.

CMSX-4 alloy is a second generation single crystal superalloy containing 3% Re. It has been extensively developed to maximize overall properties, through collaborative programs with several turbine engine companies, involving close to one hundred 400 lb. (182 kg) heats and seven 8000 lb. (3630 kg) production size heats. The alloy's aim chemistry and heat treatment (including the HIP option) have been developed to optimize microstructure and effect low levels of residual microsegregation.

Complex cooled, thin wall vane segments, often with large overhanging integral shrouds and wide chord 3-D computer designed airfoils, can be difficult and expensive to manufacture as single crystals due to grain problems, and recrystallization occurring during solution heat treatment resulting from residual casting stresses. CM 186 LC alloy, a second generation DS columnar grain superalloy containing 3% Re, has been developed with turbine engine company collaboration, with both component producibility and economic objectives particularly in mind.



Solar Mars T-14000
Single Crystal 1st Blade
CMSX-4 Alloy

Figure 1

CMSX-4 Superalloy

Chemistry

CMSX-4 alloy, developed using a multi-dimensional approach (23) over a ten year period, achieves a high level of balanced properties. The alloy is derived from CMSX-2® alloy (11, 14) and employs the beneficial strengthening effects of Re. The nominal composition and density are shown in Table II.

It is known that Re partitions mainly to the γ matrix, retards coarsening of the γ' strengthening phase and increases γ/γ' misfit (26). Atom-probe micro-analyses of Re containing modifications of PWA 1480 and CMSX-2 alloys reveal the occurrence of short range order in the γ matrix (27, 29). Small Re clusters (approximately 1.0 nm in size) are detected in the alloys. The Re clusters act as efficient obstacles against dislocation movement in the γ matrix compared to isolated solute atoms in solid solution and thereby play a significant role in improving alloy strength. Some studies have shown that approximately 20% of the Re in this type of alloy partitions to the γ' (28), thereby strengthening the γ' phase.

Lamilloy® is a registered trademark of Allison Gas Turbine Division (GMC).

The aim chemistry optimization phase for CMSX-4 alloy targeted maximization of creep-rupture response of the alloy utilizing multi-step 99%+ solution heat treatment procedures and ensuring alloy microstructural stability. Extensive experience confirms that fully solutioned microstructures may be readily attained with CMSX-4 alloy airfoils in production vacuum heat treat furnaces with no incipient melting.

Alloy Melting

The optimized vacuum induction refining (VIR) procedures developed for CMSX-2 and CMSX-3® alloys and discussed in (11), were used to produce the seven CM V-3 furnace 8000 lb. (3630 kg) heats of CMSX-4 alloy, melted to date. Table III shows the C, S, [N] and [O] contents of these heats. Studies by several SX casters demonstrate that high [N] and [O] levels in single crystal superalloy ingot adversely affect SX casting yield due to grain defects (30). The presence of [O], [N] and S master alloy impurities are known to transfer non-metallic inclusions, such as aluminum oxide and nitrides and sulfides of tantalum and titanium, to SX parts (31).

The extensive development of the vacuum induction refining process for the CMSX-4 alloy ingot combined with clean single crystal casting processes have resulted in both clean alloy and airfoil castings in terms of stable oxide dross or refractory inclusions. This is confirmed by production of tens of thousands of single crystal turbine blade castings ranging from .010" (.25 mm) thick Lamilloy crystalfoils to large shrouded turbine blades for the new 80,000 lb. thrust commercial turbofan engines, with attendant high process yields and low levels of grain defects (23).

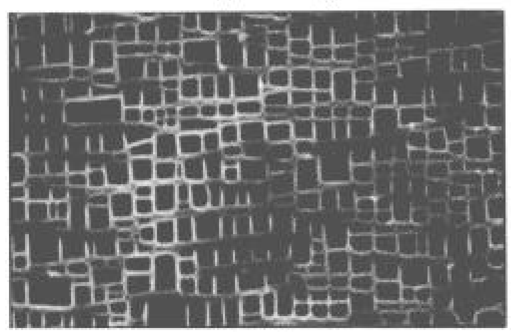
CMSX-4 Alloy 8000 lb. (3630 kg)
V-3 Furnace 100% Virgin Heats

Heat	C ppm	S ppm	[N] ppm	[O] ppm
V 7927	20	6	3	1
V 8053	19	5	2	1
V 8054	15	6	3	1
V 8154	21	3	2	2
V 8194	17	4	2	2
V 8195	18	4	2	2
V 8256	15	2	1	1

(wt. ppm)

Table III

CMSX-4 Alloy (V 8154) 2nd Stage Solid Blade SX Cast by Allison.
CM 99%+ Soln. AC + 6 hrs/2085°F (1140°C) AC + 20 hrs/1600°F (871°C) AC.
LE Airfoil Upper Longitudinal



1μm

Laboratory Fully Heat Treated Airfoil
γ' Microstructure (SEM)

Figure 2

Microstructure

Ageing heat treatment studies have been undertaken which show that the maximum creep-strength throughout the 1500°F (816°C) - 2100°F (1149°C) testing range for (001) orientation specimens, is attained with an average 0.45 μm cubic γ' aligned structure, with a 2085°F (1140°C) high temperature ageing treatment being required. The relatively high ageing temperature suggests CMSX-4 has low γ/γ' mis-fit at high temperatures. A typical fully heat treated SEM microstructure for a turbine airfoil is shown in Fig. 2. The solution treatment was undertaken in a laboratory tube furnace finishing at 2 hrs/2410°F (1321°C)/Air Cool (AC). This necessitates a 6 hrs/2085°F (1140°C)/AC age to achieve the desired γ' size. A final age of 20 hrs/1600°F (871°C)/AC is employed. Commercial single crystal turbine airfoils are vacuum solution treated utilizing a Gas Fan Quench (GFQ) from the solutioning temperature, which only necessitates a several hour 2085°F (1140°C)/GFQ high temperature age to achieve the required γ' structure.

TEM foils from a laboratory fully heat treated CMSX-4 airfoil are shown in Figs 3 and 4 (32). Fig 3 in an ordering reflection, shows that the γ' is variable in size locally and by factors (linearly) of about 3. Also, the intervening γ has similar variations in thickness with the formation of secondary, ultra fine γ' in the broader γ gaps resulting from the final 1600°F (871°C) age. EDX composition profiles of the γ' and γ in the TEM foils show the expected trends with the γ' being rich in (Ni with some Co and Cr) and (Al, Ti, Ta and W). The γ is rich in Ni, Cr, Co - disproportionally larger for Cr relative to Co - as well as of course Re and W. Recent research (33) with TEM foils - (EDX-HP Ge detector) on SRR 99 single crystal alloy (Table 1), shows some steep element concentration gradients in the γ' phase persist even with an aged 0.5 μm cubic γ' microstructure. The enrichment of Al in the γ' at the γ/γ' interfaces is still large and the reduction of Cr at the interfaces is maintained. The average concentrations of elements in the γ' phase have not changed significantly by the two stage ageing heat treatments employed. Interfacial γ/γ' chemistry is thought to be important in influencing creep response.

Laboratory Fully Heat Treated CMSX-4 Airfoil
TEM Microstructure

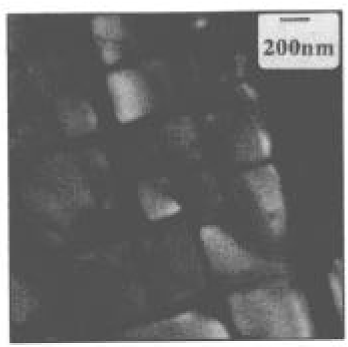


Figure 3

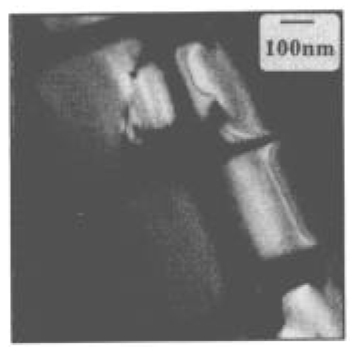


Figure 4

Research (34) has shown that for alloys with a high volume fraction of γ' (at a constant volume fraction), difficult to shear cuboidal γ' precipitates which are spaced as closely as possible will provide optimum creep resistance. Any compositional adjustment which influences the level of misfit between the γ and γ', the chemistry of the γ', the equilibrium volume fraction of γ', or its coarsening behaviour, will have major resultant effect on creep properties, by changing γ' morphology or shape or the matrix gap dimension.

Creep-Rupture and Phase Stability

The stress-rupture temperature capability advantage of CMSX-4 alloy over CMSX-2/3 alloys is 64°F (35°C), based on density corrected average properties, in the 36 ksi/1800°F (248 MPa/982°C) testing regime (23). The data also suggest that CMSX-4 alloy has useful strength at 2100°F (1149°C) (23). The Larson-Miller stress-rupture data base generated by CM includes over 175 data points from nine heats, including six 8000 lb (3630 kg) heats. These properties were undertaken on both .187" dia. (4.8 mm) test bar and .070" dia. (1.8 mm) machined-from-blade (MFB) specimens, with no fall-off in properties apparent with production heat scale-up to 8000 lbs (3630 kg).

Industrial gas turbine applications for the alloy has necessitated creep-rupture testing out to 4000 hours rupture life at 20 ksi/1800°F (138 MPa/982°C). The 1800°F (982°C) stress-rupture data shown in the log-stress to log-life plot in Fig. 5 shows no fall-off in properties due to undesirable microstructural changes.

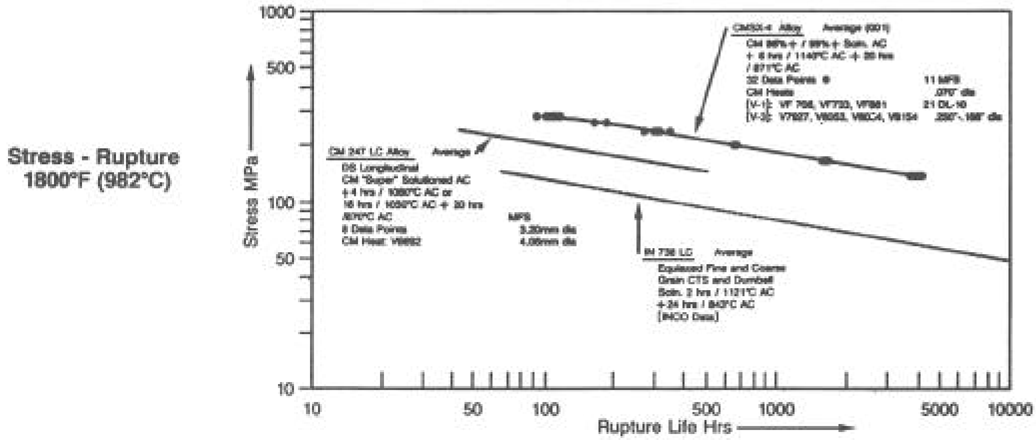


Figure 5

Microstructures of a post-test (.25" dia. (6.4 mm)) specimen creep-rupture tested at 20 ksi/1800°F (138 MPa/982°C)/3921 hrs t_r are shown in Figs 6 & 7 (32). The generally irregular format of the agglomerated γ/γ' structure is apparent. Extremely small (700 nm (0.7 μm)) rhombohedral topological intermetallic phases surrounded by γ' can just be discerned at (A) in Fig 7. Analytical TEM shows these phases to be ((Ni, Co) W) (Cr, Re) rich (32). However, no creep cracking has been found to be associated with these phases. It is postulated in (35) that the development of a range of extremely small heterogeneity in Re containing single crystal or DS superalloys during creep can be of fundamental importance to the improvement of creep behavior.

CMSX-4 Post-test TEM Microstructure
20 ksi/1800°F
(138 MPa/982°C)/3921 hrs_{t_r}

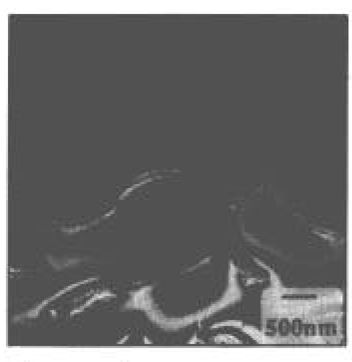


Figure 6

Figure 7 [Optical]

Mechanical Fatigue

The absence of significant residual γ/γ' eutectic phase, carbides, oxide, nitride or sulphide inclusions & microporosity (resulting from the ability to readily fully solution CMSX-4 and HIP) (Figs 8 & 9), results in remarkably high mechanical fatigue properties, with smooth and in particular notched specimens. At 1382°F (750°C) the smooth specimen

HCF strength of CMSX-4 to 10^7 cycles Nf, is improved by 50% by HIP. HIP'ing CMSX-4 results in significantly greater mechanical fatigue property improvements compared to that attained with non-Re containing alloys, indicating that the elimination of the micropores is not only the important factor. Increased refractory element (W, Re & Ta) homogeneity may also be relevant. Additionally, the superior creep strength of CMSX-4 alloy over first generation single crystal alloys is expected to be a significant advantage in HCF conditions where sufficient time is spent at stress and temperature to enable creep-fatigue interactions to occur (17).

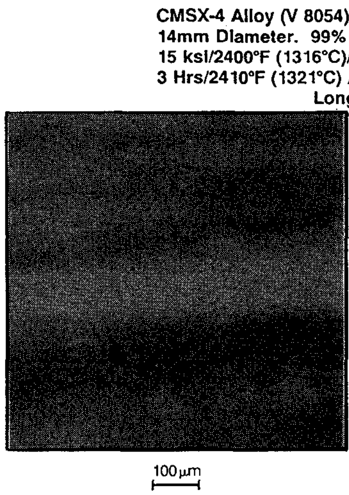


Figure 8

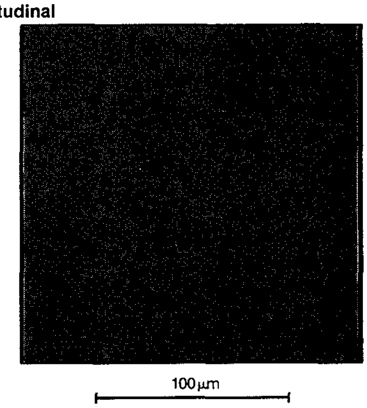


Figure 9

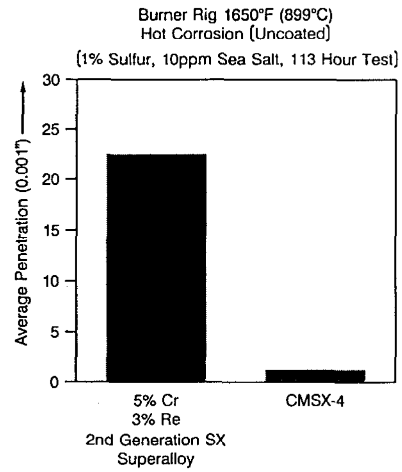


Figure 10

Oxidation and Hot Corrosion

Cyclic burner rig testing has shown CMSX-4 to have excellent high temperature bare oxidation resistance (23). Burner rig sulphidation testing under a variety of Type I hot corrosion test conditions (e.g. Fig 10) show the alloy to have performance similar to IN 792 in longer term testing.

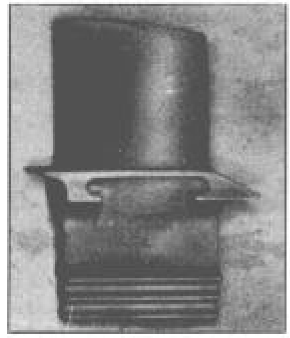
Industrial Gas Turbine Experience

CMSX-4 alloy was introduced for turbine blading in the Solar Turbines Inc. Mars T-14000 engine in 1990. This resulted from the need for increased durability in the uprated Mars engine. The initial engine field test was performed at a natural gas pipeline station where the engine was used to drive a Solar C-601 gas compressor set. In this engine the first stage turbine rotor (Fig 11) had a "rainbow" set of blades with test variables which included blade alloy, (CMSX-4 and equiaxed MAR M 247) coatings, cooling flow and minor blade geometrical differences. The engine was removed for inspection after accumulating 4,333 service hours and 44 starts. The engine was fueled on natural gas.

During tear down inspection it was observed the blades were in good condition. Typical as-received and after-test blades are shown in Fig 1 and Fig 12. Representative components were removed for detailed metallurgical evaluation and replaced with new parts. The remaining hot section components were replaced in the engine with the plan to continue the engine test for a total of 20,000 hours. At the time of writing they have accumulated an additional 4,000-5,000 hours in the engine at full rated conditions.

Solar Mars T-14000 1st Stage turbine assembly - CMSX-4 blades

Figure 11



Solar Mars T-14000 1st blade in CMSX-4 after 4,333 service hours

Figure 12

Metallographic sections of removed blades were prepared at tip and 70% span locations to determine their condition after the 4,333 hours of engine operation. The results may be summarized as follows:

As shown by radial sections, blade tip integrity was better for the CMSX-4 blades in both coated and uncoated conditions compared to the standard MAR M 247 blades. As anticipated, none of the platinum aluminide coated blades showed any significant oxidation. For uncoated blades, maximum depth of oxidation was greater for the MAR M 247 compared to the CMSX-4 blades and was related to the more rapid attack along grain boundaries and MC carbides. Interdiffusion of coating and substrate occurred to a lesser extent with the CMSX-4 blades.

Coarsening of the γ' and rafting was observed in the CMSX-4 SX blades at locations corresponding to extreme high temperatures and in MAR M 247 blades at locations corresponding to lower temperatures in the 1700°F (927°C) range and above.

Acicular phases were formed at the coating/substrate interface (diffusion zone) in both MAR M 247 and CMSX-4 alloys. In general, the incidence of these phases was greater in the MAR M 247 and occurred in lower temperature locations in the blades. For example, acicular phases were observed at the 70% span locations of the MAR M 247 blades, whereas at the same locations of the SX blades, roughly spherical particles of a Re/Cr/W rich phase were present at the coating/substrate interface.

A very small amount of acicular phase formation occurred within the bulk sections of the CMSX-4 blades in the dendrite central regions. In this context it should be noted that the original heat treat schedule comprising the lower temperature primary age (1975°F (1080°C) vs. 2085°F (1140°C)) was used for the SX parts.

CMSX-4 is currently bill-of-material in production versions of the Mars T-14000 engine with an estimated 80,000 total hours of successful running time so far accumulated.

CM 186 LC Superalloy

Vane component design is tending toward more complex cooling configurations with thin walls (.020" (.5 mm)) to improve engine efficiency through reduced use of cooling air. These complex vane segments can be difficult and expensive to manufacture as single crystals. CM 186 LC alloy, a second generation DS, columnar grain superalloy has been developed with both component producibility and economic objectives particularly in mind. The nominal composition and some of the critical tramp element chemistry of the first 8000 lb (3630 kg) CM V-3 furnace heat of the alloy is shown in Tables IV and V The chemistry concepts for excellent DS

CM 186 LC Alloy

Nominal Composition, wt. %													
C	Cr	Co	Mo	W	Ta	Re	Al	Ti	B	Zr	Hf	Ni	Density kg/dm³
.07	6	9	.5	8	3	3	5.7	.7	.015	.005	1.4	BAL	8.70

Table IV

CM 186 LC Alloy V-3 Furnace	8000 lb. (3630 kg) 100% Virgin Heat		
	wt. % or ppm		
Heat	C	S ppm	[N] ppm	[O] ppm
V 8127	.069	4	1	1

Table V

castability were developed for CM 247 LC® alloy (13) and further refined for the higher strength Re containing alloy. The alloy's DS castability, in terms of freedom from DS grain boundary cracking, is confirmed to be excellent, particularly in casting advanced first stage vanes for a new turbofan engine, where cracking and tearing problems are encountered with a lower strength, established first generation DS alloy. CM 186 LC alloy is used in the as-cast and double aged condition which confers DS longitudinal creep-rupture properties equivalent to first generation single crystal alloys CMSX-2 and CMSX-3 up to 1800°F (982°C). Strength at higher temperatures lies between CMSX-2/3 and the solution treated DS alloy CM 247 LC (Fig 13). The absence of a solution treatment requirement with CM 186 LC DS vanes removes the recrystallization problem and reduces process costs. The family derivation ensures that CM 186 LC alloy can be manufactured from virgin/CMSX-2, -3 or -4 foundry revert blends further improving economics of manufacture.

Larson-Miller Stress-Rupture
DS Longitudinal
CM 186 LC vs. CM 247 LC
vs. CMSX-2/3 (001)

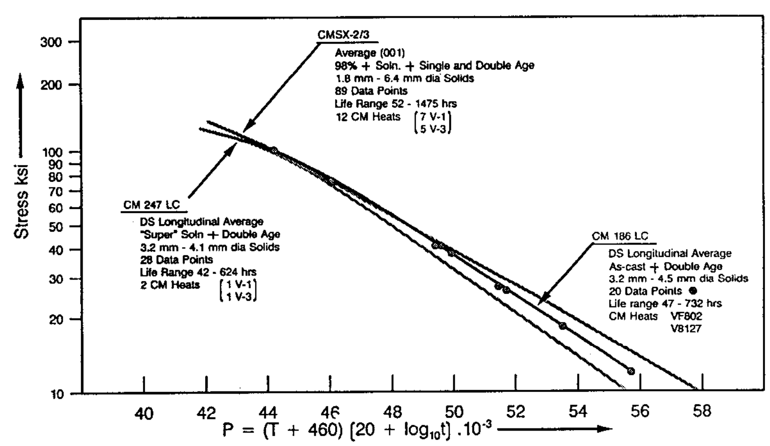


Figure 13

DS transverse stress-rupture ductility of CM 186 LC in the ductility trough region at 55 ksi/1600°F (379 MPa/871°C) is typically 9% elongation in 4D. Satisfactory phase stability has been demonstrated to 3500 hrs rupture life at 21.76 ksi/1742°F (150 MPa/950°C) and 400 hrs rupture life at 12 ksi/2000°F (83 MPa/1093°C).

CM 186 LC alloy has been successfully scaled to a 8000 lb. (3630 kg) production size heat and the performance of a 50% virgin/50% CMSX-4 foundry revert heat validated. Oxidation, Type I hot corrosion (sulphidation) and coating performance has been shown on cyclic burner rig testing to be very similar to MAR M 247 alloy.

MAR M is a trademark of Martin Marietta Corporation.

Conclusions

Turbine blade engine test evaluation by Solar Turbines Inc. confirms the overall properties of CMSX-4 alloy displayed during the laboratory evaluation testing. The beneficial role of Re in contributing to the overall properties of the alloy are clearly apparent.

CM 186 LC alloy has demonstrated DS vane producibility and overall mechanical and environmental property results to justify turbine engine test evaluation scheduled to commence late 1992.

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