MAR M 247 DERIVATIONS - CM 247 LC DS ALLOY
CMSX SINGLE CRYSTAL ALLOYS
PROPERTIES & PERFORMANCE

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Summary

CM 247 LC is a chemistry modified superalloy derived in late 1978 from the MAR M 247 composition, specifically designed for directionally solidified (DS) blade and vane applications. The modified alloy demonstrates exceptional resistance to grain boundary cracking during DS casting, advanced complex cored, thin wall airfoils, combined with improved carbide microstructure, carbide stability and ductility relative to the parent, MAR M 247. Solution heat treatment studies undertaken on DS cast material show the capability of solution treating up to relatively high 1250°C (2282°F) conditions, thereby maximizing solutioning of the γ' with attendant improvements in creep-strength. DS castability and mechanical property data (stress-rupture, tensile and fatigue) are presented.

A series of complementary single crystal (SX) alloys, developed commencing in mid-1979 from the MAR M 247 composition, provide high creep strength, good SX castability, practical solution heat treatment ranges which assist in optimizing microstructure, high γ' solvus temperatures and good alloy stability. These alloys individually designated CMSX-2, CMSX-3 and CMSX-4 are also designed to have excellent high temperature bare oxidation resistance and coating performance. Environmental and mechanical property studies (both static and cyclic) are reported. Initial turbine engine test data is reported, in relation to environmental response.

Introduction

MAR M 247* is a nickel-base, vacuum melted, cast superalloy with a high γ' [Ni_3 (Al, Ti . .)] volume fraction (62%) and high refractory element (Ta + W + Mo) content (13.7 wt. %). The nominal composition is shown in Fig. 1. The alloy, developed in the very early 1970's by Danesi, Lund and others at Martin Metals Corporation, demonstrates high creep strength and good castability along with excellent oxidation resistance resulting in increasing application in turbine engines. The alloy, as originally developed for conventionally cast equiaxed turbine blade and vane parts, is not optimized for DS casting technology.

DS component casting technology (1, 2, 3, 18), pioneered by Pratt & Whitney Aircraft and developed to achieve significant increases in creep strength/temperature capability, thermal fatigue properties and component durability, is seeing increasing application in modern turbine engines. Aside from the addition of Hf (4, 5) (developed by Martin Metals) to nickel-base cast superalloys to initially assist intermediate temperature ductility of equiaxed castings and later DS castability in terms of reducing grain boundary cracking problems, little emphasis is placed on alloy development specifically for DS part applications. An exception is the development of René 150 alloy (6). Continuing improvements to airfoil cooling techniques result in significant gains in gas turbine operating efficiencies. These cooling techniques usually result in very complex cored, thin wall [.020" (0.5 mm) - .040" (1 mm)] airfoil designs, which are susceptible to grain boundary cracking during DS casting high creep strength alloys, particularly with modern high thermal gradient casting processes. CM 247 LC, developed from the MAR M 247 base composition at the request of a turbine engine company (Ack. 1) during 1978, is intended to eliminate the DS grain boundary cracking problem. The advent of single crystal technology is not likely, in the intermediate term, to remove the need for DS airfoil components. DS airfoils will continue to be used for vane segments, second and low pressure stage blades in advanced turbine engines because of cost effective considerations.

MAR-M-247*
NOMINAL COMPOSITION
(Wt. %)

C	0.15	Al	5.5
Cr	8.4	Ti	1.0
Co	10.0	Hf	1.5
W	10.0	B	0.015
Mo	0.7	Zr	0.05
Ta	3.0	Ni	Balance

Density-0.308 lbs/cu. in.
(8.54 gms/cc)

Figure 1.

Single crystal superalloy and component casting technology (7, 8), pioneered by Pratt & Whitney Aircraft, achieves further significant increases in creep strength/temperature capability and component durability. However, little alloy development emphasis is evident in terms of component producibility, particularly single crystal alloy castability and solution heat treatment, with some of the initial alloys developed. The low Ta/high W ratio alloys are found to be "freckle" sensitive (Ack. 2 and Ack. 3), particularly when cast into larger parts with lower thermal gradient casting processes. NASAIR Alloy 3 (Ref. 8), which contains a deliberate Hf addition to improve coated oxidation/corrosion resistance, is characterized by a very narrow solution heat treatment range [11°C (20°F)]. Commercial producibility of these components is an important factor.

The second generation oxidation resistant single crystal superalloys (7, 9) being introduced as turbine blade and airfoil materials show a 25°C (45°F) to 50°C (90°F) temperature capability improvement, in terms of time to 1% creep, compared to the long used DS MAR M 200 Hf alloy. The creep property improvement, which increases with increasing temperature/decreasing stress, is based on optimized single crystal microstructures with full solutioning of the as-cast coarse γ'. The ability to attain the fully solutioned microstructures containing 65-68 volume % of re-precipitated fine, coherent γ' with an average size of 0.45 microns or less, to maximize creep response, depends upon the alloy's solution heat treatment range (difference between the γ' solvus and incipient melting temperatures), the cooling rate from the solution temperature (8) and also response to new aging treatments (10).

CMSX-2 and CMSX-3 single crystal superalloys are derivatives of the MAR M 247 composition and demonstrate an attractive combination of properties for advanced technology turbine blade and vane airfoil components. CMSX-4 is a third generation, ultra high strength single crystal superalloy developed for small gas turbines. This range of complementary single crystal superalloys is designed for high temperature, oxidation environment turbine applications.

CM 247 LC

DS Chemistry Modifications

The addition of Hf to high strength cast superalloys is used to combat DS grain boundary cracking problems, with levels of 2% and greater being common. Increasing levels of Hf, unfortunately, increase component rejection rate and quality assurance problems due to the occurrence of HfO inclusions in the DS components usually resulting from Hf/ceramic core/shell reactions.

Zr and Si are known, in general, to be "bad actors" with respect to DS grain boundary cracking [small amounts of a Hf rich eutectic phase containing high concentrations of Zr and Si found in DS crack prone tests (13)]. It is also now apparent that very small reductions in Zr and Ti contents, combined with very tight control of Si and S, dramatically reduce the DS grain boundary cracking tendency of a high creep strength superalloy such as MAR M 247. The major microstructural effect of the lower Ti content in CM 247 LC, compared to MAR M 247, is to significantly reduce the size of the γ / γ' eutectic nodules, as noted in (14), and also to lower the volume fraction of the eutectic from approximately 4% in MAR M 247 to 3% in CM 247 LC DS components. This factor is also believed to be significant in reducing the DS grain boundary cracking tendency of CM 247 LC.

The chemistry modifications incorporated in CM 247 LC alloy are based on CM practical experience with grain boundary cracking problems in DS alloys, the use of the inductively coupled plasma (ICP) analytical technique for very accurate determination of Zr chemistry at low levels, and on earlier published CM work on MAR M 247 alloy (11, 12). The chemistry changes and objectives are summarized as follows:

Table I.

	MAR M 247	CM 247 LC	
Lower Zr	.03%	.015%	- Eliminate grain boundary cracking during DS casting thin wall parts.
Lower Ti	1.0%	.7%	
Tightly control Si	.10% max	.03% max	
Tightly control S	150 ppm max	15 ppm max	
	MAR M 247	CM 247 LC	
Lower C	.15%	.07%	- Improve carbide microstructure, carbide stability and RT to intermediate temperature ductility.

Studies undertaken in 1979 (22) show that lowering the carbon from .17 to .08% alone in a similar high creep stength cast superalloy (MAR M 002) does not change the DS grain boundary cracking tendency. The cracking susceptibility increases as the carbon is lowered to the .08 - .02% range. This is thought to be due to increasing amounts and size of eutectic nodule formation due to the freeing of Ti resulting from the lower C content.

Table II.

	MAR M 247	CM 247 LC	
Lower W	10.0%	9.5%	- Minimize M_6C (M is W, Mo) platelet formation after high temperature solution treatment & subsequent [982°C (1800°F)] stressed exposure.

Hf is retained at a moderate 1.4% level to assist grain boundary strength and ductility without HfO inclusion problems. The Cr is lowered from 8.4% to 8.1% and combined with the lower Ti, W and Mo levels more than compensates for the lower carbon to further ensure CM 247 LC alloy is free from sigma (σ) phase. Phacomp chemistry control is also introduced to ensure CM 247 LC is free from σ phase formation.

DS Castability

A 250 lb. (113 kg) V-1 VIM furnace heat (VF-165), produced in 1978, precisely conforms to the CM 247 LC aim chemistry, the nominal composition of the alloy being shown in Fig. 2.

CM 247 LC
NOMINAL COMPOSITION
(Wt. %)

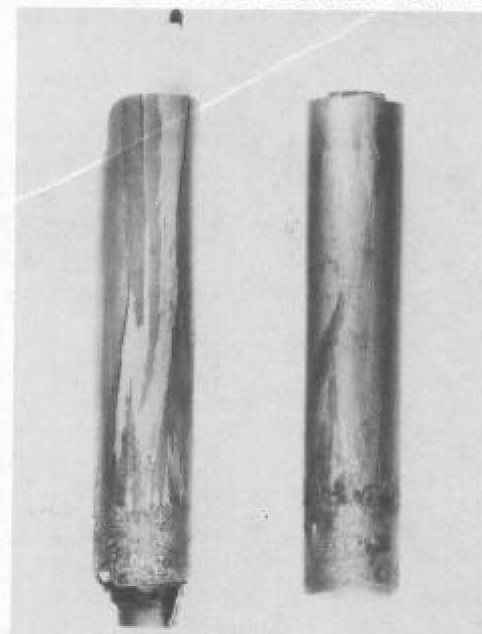
C	0.07	Al	5.6
Cr	8.1	Ti	0.7
Co	9.2	Hf	1.4
W	9.5	B	0.015
Mo	0.5	Zr	0.015
Ta	3.2	Ni	Balance

Density-0.306 lbs./cu. in.
(8.50 gms/cc)

Figure 2.

The DS grain boundary cracking test, developed by Ack. 1, is a hollow tube of the alloy being tested. As the tube is DS cast, it shrinks around the alumina core and the resultant strain (approx. 2%) results in grain boundary cracking of sensitive alloys. The ratings range from A (no cracks) to F (catastrophic cracking). This is a particularly severe DS grain boundary cracking test. CM 247 LC Heat VF 165 achieves an excellent A-B rating in this test (2 specimens each alloy) compared to an E rating for MAR M 247, as shown in Fig. 3. The testing and alloy rating being undertaken by Ack. 1. Heat VF 165, when cast into DS "crack prone" complex cored, thin wall blades using a relatively high thermal gradient casting process (3, 18), demonstrates no grain boundary cracking, even using casting conditions known to enhance cracking. The CM 247 LC DS blades also show very low levels of microporosity - all fields $\leqslant$ 0.2% and most 0.1%. High thermal gradient DS casting processes are attractive since they reduce secondary dendrite arm spacing / microsegregation and subsequently enhance γ' solution heat treat capability.

DS GRAIN BOUNDARY CRACKING TEST RESULTS



MAR M 247 HEAT VE 930 **CM 247 LC HEAT VF 165**

Figure 3.

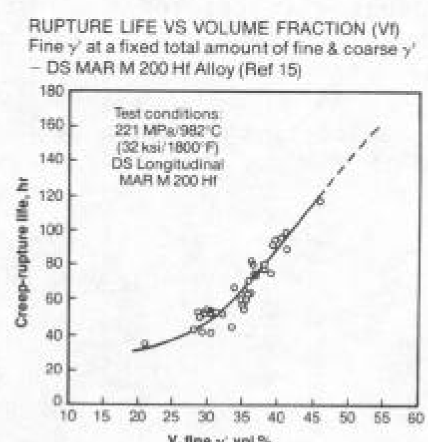


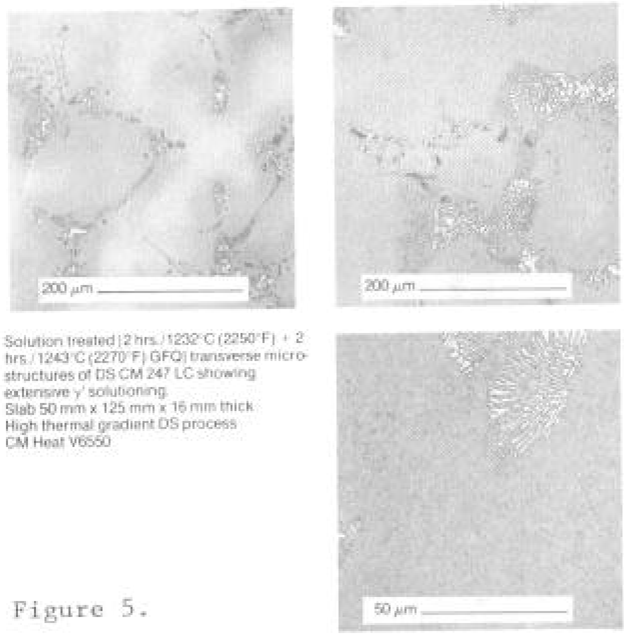
Figure 4.

Alloy Stability

Furnace soaking evaluation of CM 247 LC (Heat VF 165) and MAR M 247 (Heat V5224) DS specimens at 850°C (1560°C), 950°C (1740°F) and 1050°C (1920°F) for up to 3000 hrs. in the as-cast and 1221°C (2230°F) solutioned condition, shows CM 247 LC free from σ phase, and much less susceptible to M_6C platelet formation compared to MAR M 247. These results are detailed in (14), the work being undertaken by Ack. 4.

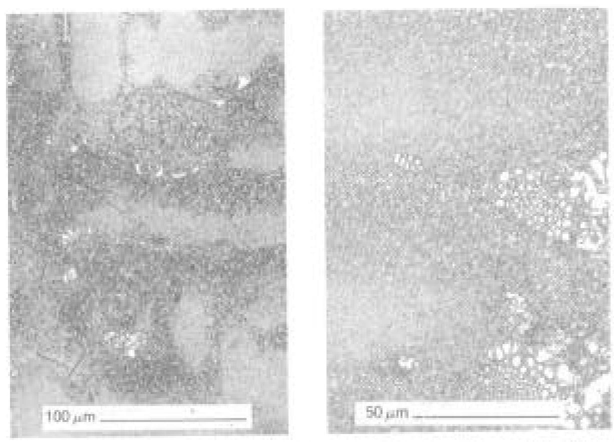
Solution Heat Treatment

Solution heat treatment studies (15) on DS MAR M 200 Hf show that creep strength is a direct function of the volume fraction of solutioned and re-precipitated fine γ' (Fig. 4). It is apparent from the chemistry changes that DS CM 247 LC has a significantly higher incipient melting point than DS MAR M 247. With the advent of vacuum heat treatment furnaces with close control of temperature, developed for narrow solution heat treatment range SX alloys, it is possible with pre-homogenization step heat treatments to solution DS CM 247 LC at temperatures up to 1250°C (2282°F) without incipient melting. The more extensive degree of γ' solutioning, achievable with CM 247 LC without incipient melting, is shown in Fig. 5 compared with solutioned DS MAR M 247 (Fig. 6). DS MAR M 247 is normally restricted to a 1221°C (2230°F) solutioning temperature because of its lower incipient melting point.



Solution treated [2 hrs./1232°C (2250°F) + 2 hrs./1243°C (2270°F) GFQ] transverse microstructures of DS CM 247 LC showing extensive γ' solutioning.
Slab 50 mm x 125 mm x 16 mm thick.
High thermal gradient DS process.
CM Heat V6550

Figure 5.



Solution treated [2 hrs./1221°C (2230°F) GFQ] longitudinal microstructures of DS MAR M 247 showing partial γ' solutioning.
Blade airfoil—section size 3 mm, low thermal gradient DS process.

Figure 6.

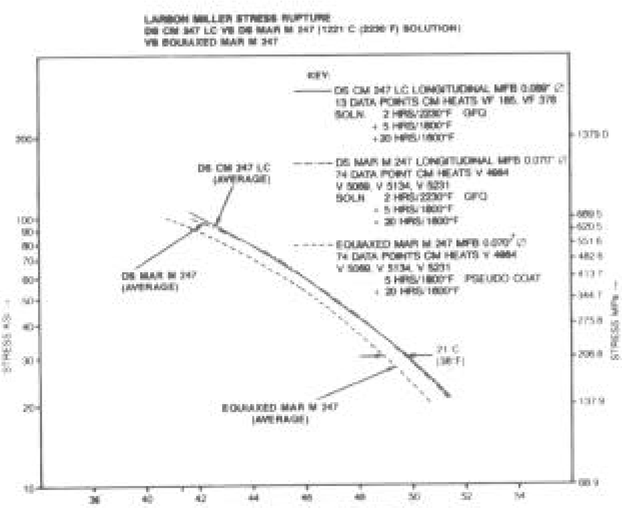


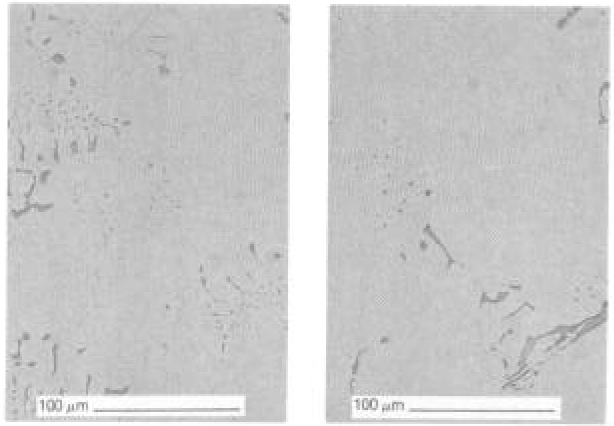
Figure 7.

Mechanical Properties

Stress-Rupture. Transverse MFB stress-rupture testing at 850°C (1560°F) and 1040°C (1900°F) by Ack. 4 shows DS CM 247 LC and DS MAR M 247 to have similar life and ductility, thus showing that the improved DS grain boundary cracking resistance is attained without sacrificing transverse stress-rupture properties.

The Larson-Miller plot (Fig. 7) shows the DS longitudinal stress-rupture properties of CM 247 LC and MAR M 247 are very similar. The CM 247 LC data was generated using relatively high thermal gradient DS casting processes at Ack. 4 & 5, and the MAR M 247 data utilized a lower gradient casting process at Ack. 2, 1221°C (2230°F) solution conditions being used for both alloys. Current work at CM to "super-solution" DS CM 247 LC is expected to significantly increase both creep- and stress-rupture properties (23).

Tensile. The longitudinal DS data (Table III) comparing CM 247 LC and MAR M 247 at 650°C (1200°F), 750°C (1380°F) and 850°C (1560°F) shows both alloys to have similar strength, with CM 247 LC demonstrating over 50% greater tensile ductility due to its more favorable carbide (Fig. 8) and γ/γ' eutectic microstructure (Figs. 5 & 6).



DS MAR M 247 long solutioned 2 hrs./1221°C (2230°F) GFQ
Blade airfoil—section size 3 mm
Low thermal gradient DS process.

DS CM 247 LC trans solutioned 2 hrs./1232°C (2250°F) + 2 hrs./1243°C (2270°F) GFQ
Slab 50 mm x 125 mm x 16 mm thick
High thermal gradient DS process
CM Heat V6550

Carbide microstructures of DS MAR M 247 and DS CM 247 LC showing the lower volume fraction of carbides with CM 247 LC and smaller script-like "rosette" patterns.

Figure 8.

Table III.
CM 247 LC & MAR M 247
DS Longitudinal Tensile Data (Ack. 4)
Aged Only [20 hrs/871°C (1600°F)]

Alloy/Heat		Test Temp.	0.2% Proof Stress MPa (ksi)	Tensile Strength MPa (ksi)	Elong. %	RA %
CM 247 LC	VF165	650°C	754 (109.3)	919 (133.3)	11.5	9.5
MAR M 247	V5224	(1200°F)	746 (108.2)	857 (124.3)	6.4	8.1
CM 247 LC	VF165	750°C	794 (115.3)	1000 (145.0)	8.1	4.3
MAR M 247	V5224	(1380°F)	813 (118.0)	937 (136.0)	5.5	6.5
CM 247 LC	VF165	850°C	839 (121.6)	870 (126.1)	10.5	12.5
MAR M 247	V5224	(1560°F)	839 (121.6)	865 (125.4)	6.9	6.0

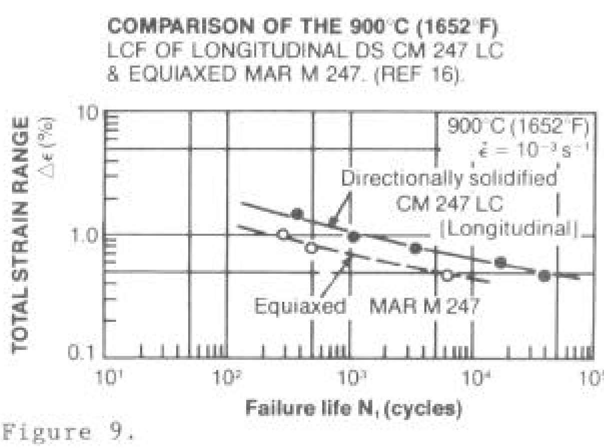


Figure 9.

Fatigue. Extensive fatigue test data on DS CM 247 LC is reported in (16, 17). Based on 1.5 mm (.060") wall, tubular specimen testing undertaken by Ack. 6, the 900°C (1652°F) low-cycle fatigue (LCF) life of longitudinal DS CM 247 LC is increased more than five times compared to equiaxed MAR M 247 (Fig. 9). The primary cause of this improvement is the absence of grain boundaries perpendicular to the loading axis. However, the increased intrinsic tensile ductility of CM 247 LC, and also less microporosity in the DS test pieces, are likely to contribute to the improvement.

Environmental Properties

Burner rig oxidation and corrosion testing of bare DS CM 247 LC shows similar results to DS MAR M 247 - both alloys are essentially oxidation resistant superalloy materials. It is postulated that DS CM 247 LC may show some advantages in terms of coating life due to the smaller script-like carbide colonies compared to DS MAR M 247 (Fig. 9) - these carbide "rosette" patterns are often associated with coating breakdown.

Scale-up

A total of 12 V-1 furnace VIM heats of CM 247 LC (113-181 kgs each) are utilized in this development program, with deliberate small variations made to C, Ti and Cr to study and optimize alloy aim chemistry. A firm chemistry specification range is now established for the alloy based on this work. Two 3630 kg (8000 lb.) V-3 furnace production scale-up heats have now been successfully produced during separate furnace lining campaigns and demonstrate the practicality of adhering to the tight specification range. Critical chemistries for these two heats (V6550 & V6692) are shown in Fig. 10. The DS castability, γ' solution heat treat response and creep-rupture characteristics for CM 247 LC are confirmed with these two scale-up heats.

Critical Chemistries DS CM 247 LC
3630 Kg (8000 lb) Production Heats - 100% Virgin
Wt. % or ppm*

Heat	Zr	Ti	Si	C	S*	[N]*	[O]*
V6550	.020	.70	.007	.071	6	2	1
V6692	.018	.69	.003	.070	5	3	3

Figure 10.

CMSX-2
NOMINAL COMPOSITION
(Wt. %)

Cr	8	Al	5.6
Co	4.6	Ti	1.0
W	8	Ta	6
Mo	.6	Ni	Balance

Density-0.311 lbs./cu. in.
(8.62 gms/cc)

Figure 11.

CMSX-2, CMSX-3 and CMSX-4 Single Crystal Alloys

Firm chemistry specification ranges are established for CMSX-2 and CMSX-3 alloys (nominal compositions shown in Figs. 11 & 12) utilizing extensive evaluation and performance data from 17 heats of CMSX-2 [including two scale-up 3630 kg (8000 lb.) heats] and 16 heats of CMSX-3 [including one scale-up 3630 kg (8000 lb.) heat]. C, S, [N] and [O] data from the scale-up heats is shown in Fig. 13. Studies undertaken by Ack. 8 & 9 show high [N] and [O] levels in single crystal superalloy ingot adversely affect SX casting grain yield, supporting the importance for low [N] & [O] levels in the master alloy. C, S, [N] & [O] master alloy impurities are shown to transfer nonmetallic inclusions, such as Al_2O_3, (Ti, Ta) C/N, and $(Ti, Ta)_x$ S, to SX parts (24).

CMSX-3
NOMINAL COMPOSITION
(Wt. %)

Cr	8	Ti	1.0
Co	4.6	Ta	6
W	8	Hf	.10
Mo	.6	Ni	Balance
Al	5.6		

Density-0.311 lbs./cu. in.
(8.63 gms/cc)

Figure 12.

CMSX-2 & CMSX-3 3630 kg (8000 lb)
V-3 Furnace 100% Virgin Heats
C, S, [N] & [O] Contents (wt. ppm)

Alloy	Heat	C ppm	S ppm	[N] ppm	[O] ppm
CMSX-2	V6527	28	5	4	2
CMSX-2	V6691	15	7	3	2
CMSX-3	V6670	24	6	4	2

Figure 13.

Since the characteristics of the CMSX oxidation resistant single crystal alloys are extensively reported and discussed in (9, 19), this paper will only briefly present and review new data.

Mechanical Properties

Recent work illustrates the importance of achieving a fully solutioned γ' microstructure in single crystal superalloy components. Fig. 14 shows that residual coarse γ' in the microstructure (cast using a low thermal gradient process) almost halves the time to 1.0% creep at 248 MPa/982°C (36 ksi/1800°F), compared to a fully solutioned γ' microstructure [cast using a high thermal gradient process (20)], from the same heat.

Environmental Properties

Results of Pt/aluminide coated (45 μm thickness), static 850°C (1562°F) salt corrosion/1000°C (1832°F) oxidation studies on CMSX-2 and CMSX-3 alloys in comparison to equiaxed IN 100 and DS MAR M 002 are shown in Fig. 15 (Ack. 7). It is apparent that CMSX-2 and CMSX-3 have excellent Pt/aluminide coating performance under these conditions, which is believed to be intrinsic in their composition, and in particular, their Al & Ti content and Ta level, which inhibit diffusion of Al from the coating into the base alloy. The Cr contents are also a rational 8%. Noteworthy is the slightly improved performance of CMSX-3 due to its .1% Hf, compared to CMSX-2 with this particular coating. However, dynamic (burner rig) aluminide coated oxidation results (Fig. 16) of CMSX-2 and CMSX-3 at 1050°C

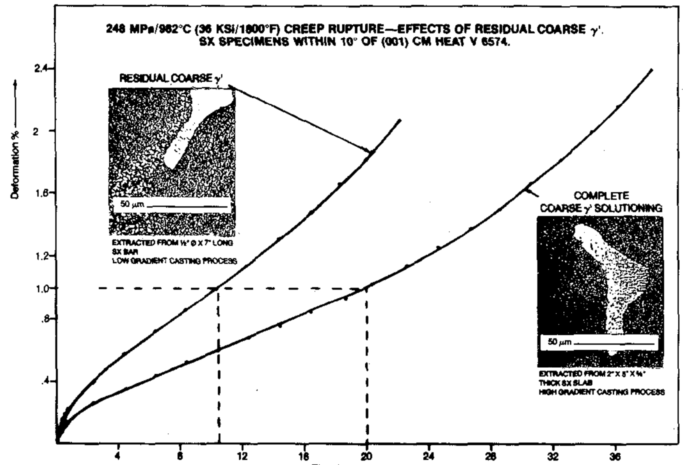


Figure 14.

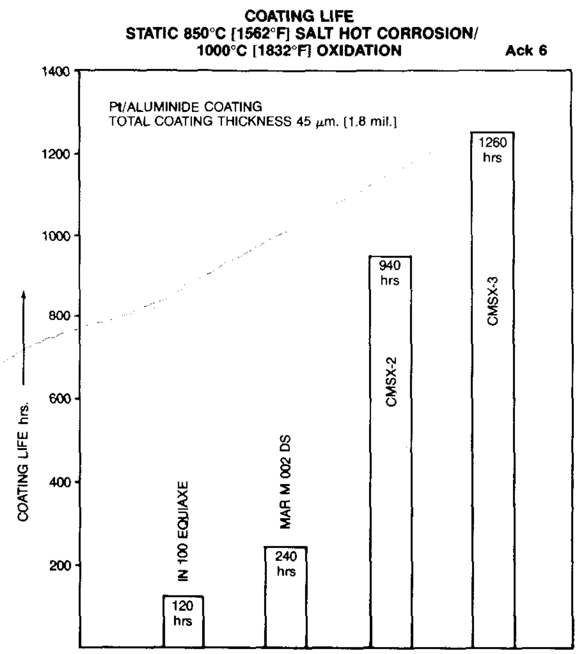


Figure 15.

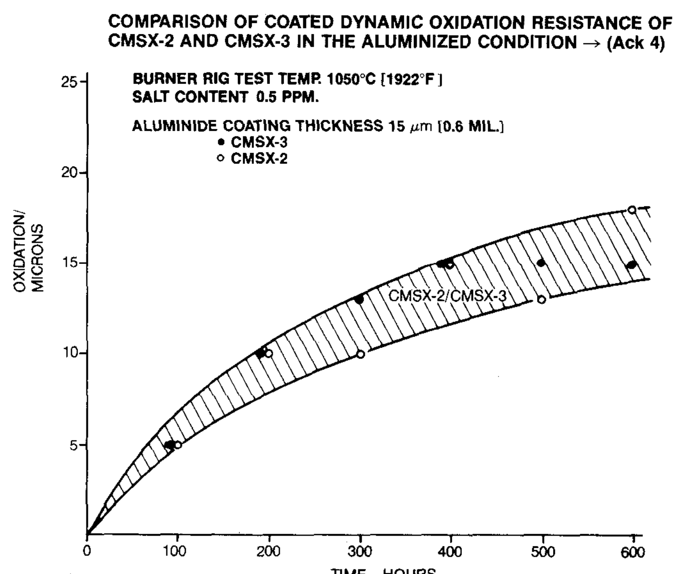


Figure 16.

(1922°F) show both alloys to give the same coating performance (Ack. 4). This points to recent studies to optimize single crystal superalloy/coating combinations for gas turbine applications (21).

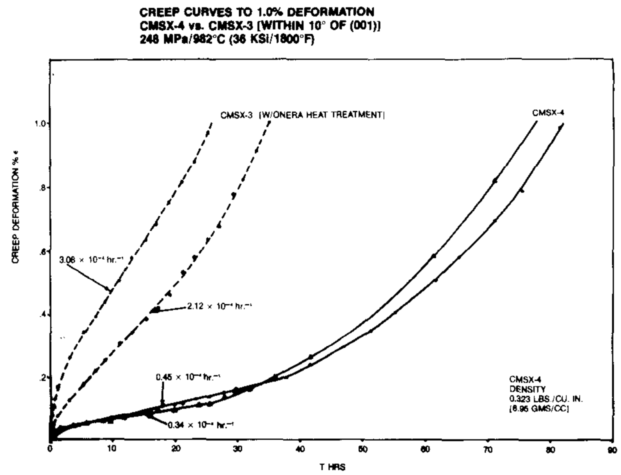


Figure 17.

Turbine Engine Testing

CMSX-2 and CMSX-3 shroudless, thin wall, complex cooled HP turbine blades after 300 cycles of extreme high temperature turbine engine testing, particularly the blade tip regions, are in excellent condition, and are reinstalled in the engine for further cyclic durability evaluation. DS blades of the same configuration in MAR M 002 had to be withdrawn at the 300 cycles due to gross tip oxidation. CMSX-4 testing is scheduled for commencement in Spring 1984 alongside CMSX-2 & 3 and will be continued until a comparison between the performance of the CMSX alloys can be determined.

Scale-up

The single crystal superalloy vacuum induction refining technology, developed on the V-1 developmental furnace, is very successfully scaled-up to a total of three 3630 kg (8000 lb.) V-3 furnace production size heats of CMSX-2 & CMSX-3 alloys, with excellent C, [N], [O] & S control as shown in Fig. 13. The SX foundry performance is confirmed with the production size heats, using 12 different SX casting processes, as are solution heat treat/fully solutioned γ' microstructure attainment, casting chemistry control and mechanical property response. Mechanical property specifications are now current for CMSX-2 and CMSX-3 alloys (Ack. 10, 11, 12, 13 & 14).

Conclusions

A complementary series of DS & SX high creep strength, oxidation resistant turbine blade and vane superalloys are developed from the MAR M 247 composition. Extensive evaluation, including turbine engine testing of DS CM 247 LC, CMSX-2 and CMSX-3 alloys by as many as 10 turbine engine companies, is verifying the attractive performance characteristics from initial developmental 181 kg. (400 lb.) heats to 3630 kg (8000 lb.) production size heats. Applications for the alloys are developing and depend on the final results of turbine engine testing in progress.

A "super strength" (Fig. 17) single crystal superalloy CMSX-4 (19) is in development for small gas turbines. Primary and secondary creep rates are much less with CMSX-4 compared to CMSX-3 with the Onera treatment (10), with a temperature capability advantage of 25°C (45°F) apparent, based on time to 1% creep at 248 MPa/982°C (36 ksi/1800°F). Time to 1% creep is a typical blade design creep criterion. Slow γ' coarsening characteristics suggest perhaps over 1100°C (2012°F) operating capability.

Nomenclature

DS - Directional Solidification
SX - Single Crystal
VIM - Vacuum Induction Melting
MFB - Machined From Blade
LCF - Low-Cycle Fatigue
Nf - Number of cycles to failure
Vf - Volume Fraction
ICP - Inductively Coupled Plasma
γ - Gamma γ' - Gamma Prime
M_6C - Platelet W, Mo rich carbide
σ - Sigma Phase
ε - Strain
$\Delta\varepsilon$ - Total strain range
* Martin Marietta Patents 3,677,747/3,720,509.

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10. Teledyne C.A.E. (Toledo)
11. Turbomeca S.A. (Bordes)
12. Garrett (Phoenix)
13. Allison (Indianapolis)
14. Williams (Walled Lake)

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