CMSX® SINGLE CRYSTAL, CM DS & INTEGRAL WHEEL ALLOYS PROPERTIES & PERFORMANCE

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ABSTRACT

The development concepts leading to the derivation of the CMSX series of single crystal superalloys from the MAR M 247 composition are reviewed in relation to castability, heat treatment, mechanical and environmental property response. Performance data are presented for CMSX-2, CMSX-3 and CMSX-4 single crystal alloys derived from 250 lb. (113 kg.) developmental heats and 8000 lb. (3630 kg.) production heats.

Directionally solidified (DS) blade and vane components have a future in advanced turbine engines due to single crystal castability problems with certain design configurations. CM 247 LC, developed specifically for thin wall, complex cooled DS blades and vanes, is now in successful flight engine service, while CM 186 LC, a Re containing derivative, is in initial development. CM 186 LC is an exceptional strength DS alloy, with longitudinal creep-rupture properties exceeding CMSX-2 and approaching CMSX-4. CM 247 LC is also in production for integral cast turbine wheels.

INTRODUCTION

Increased operating temperatures and improved efficiencies are primary goals in the continuing development of the aircraft gas turbine. A more efficient turbine is required to achieve lower fuel consumption. Higher turbine inlet temperature and increased stage loading, with fewer stages operative, result in fewer parts, shorter engine lengths and reduced weight. A reduction in engine operating cost is achieved if higher temperatures are possible without increasing part life-cycle costs.

Critical turbine components include high pressure turbine blades, vanes and discs. During the last 15 years, turbine inlet temperatures have increased by 500°F (278°C). More efficient design for air cooling of turbine blades and vanes accounts for about half this increase, with the other half brought about by improved superalloys and casting

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processes (1). The cooling now possible with serpentine cores and multi, shaped-hole, film cooling (Fig. 1) enables high pressure turbine blades and vanes to operate with turbine inlet temperatures well above the melting point of the superalloy materials. Turbine inlet temperatures as high as 2860°F (1571°C) are contemplated for several advanced fighter engines (35).

For the past 25 years, high pressure turbine blades and vanes have been made from cast Ni-base superalloys. Initially, the blades were made from isotropic equiaxed castings. Under aero turbine engine operating conditions, the failure of these equiaxed components usually occurred at the grain boundaries from a combination of creep, thermal fatigue and oxidation.

Development of the directional solidification (DS) casting process, pioneered by Pratt and Whitney Aircraft (PWA) (2, 3) to produce blades and vanes with low modulus (100) orientated columnar grains aligned parallel to the longitudinal (principle stress) axis, resulted in significant improvements in creep strength and ductility, as well as thermal fatigue resistance (5X improvement) (Fig. 2). PWA has accumulated 15 years production experience with over 20 million flight hours with DS blades and vanes (4).

Single crystal (SX) casting technology was pioneered in the mid-1960's by PWA. However, there was limited interest in the development of single crystal blades since the conventional heat treatments applied

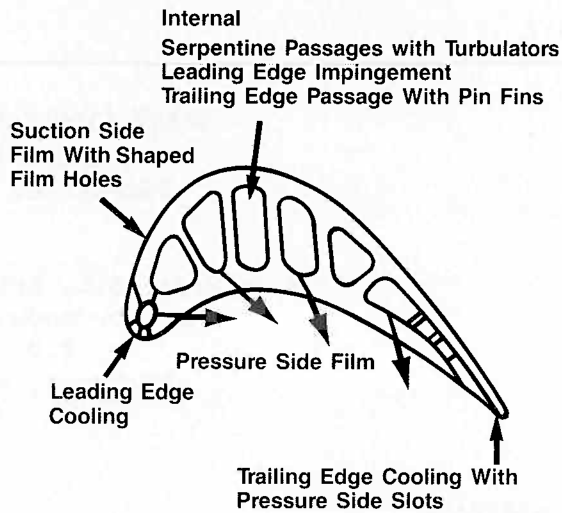


Figure 1. Turbine rotor blade cooling uses such features as shaped holes, turbulators, pin fins and other techniques.

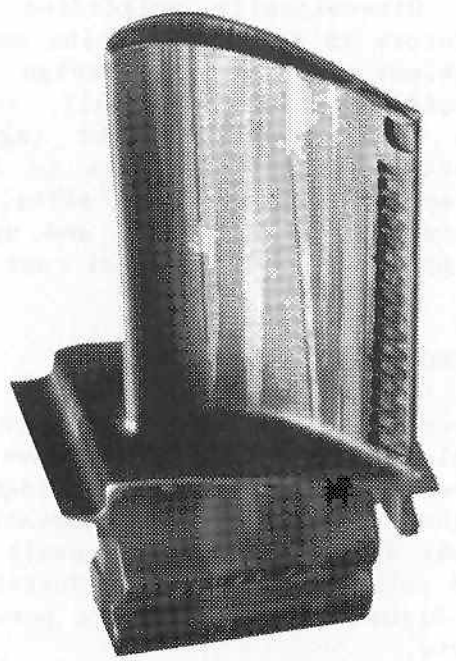


Figure 2. DS Turbine Blade CM 247 LC.

to MAR M 200 type single crystal components did not produce significant improvement in creep and thermal fatigue strength and oxidation resistance over that achieved with the DS columnar grain MAR M 200 Hf. Only ductility and transverse creep resistance were improved. It was around 1975 that the beneficial role of γ' solutioning heat treatment applied to DS MAR M 200 Hf was shown by PWA (5). It was found that creep strength is a direct function of the volume fraction of solutioned and re-precipitated fine γ' (Fig. 3). Experimental work by PWA (6) showed that the elimination of grain boundary strengthening elements (B, Hf, Zr and C) result in a substantial increase in the incipient melting temperature of the alloy. Consequently, the complete solutioning of γ' phase, with some solutioning of the γ-γ' eutectic phase, is possible without provoking incipient melting of the alloy. Single crystal alloy 454 (PWA 1480) shows a 45°F (25°C) to 90°F (50°C) temperature capability improvement in terms of time to 1% creep compared to the extensively used DS MAR M 200 Hf alloy (4). The creep property improvement, which is shown to increase with increasing temperature/decreasing stress, is based on optimized single crystal microstructures with full solutioning of the as-cast coarse γ'. Alloy 454 (PWA 1480) was developed to utilize relatively low thermal gradient single crystal casting furnaces already available as DS production units, without developing the "freckling" problems of alloy 444 (4) (single crystal MAR M 200 with no C, B, Hf, Zr and Co). Alloy 454 (PWA 1480) with its high Ta (12%), low W (4%) content is unique with this castability feature. Multi-step homogenization/solutioning treatments with tight temperature control have been developed to completely solution the γ' in alloy 454 (PWA 1480) without inducing incipient melting. PWA has now generated over 1 million flight hours of successful experience with single crystal turbine blade and vane parts in alloy 454 (PWA 1480) over the last four years (4).

RUPTURE LIFE VS VOLUME FRACTION (Vf)
Fine γ' at a fixed total amount of fine & coarse γ' – DS MAR M 200 Hf Alloy (5)

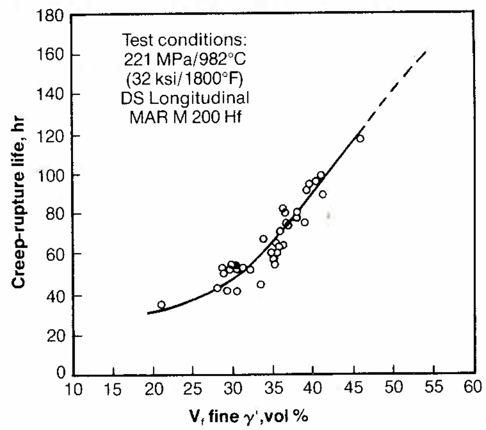


Figure 3.

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

C	0.15	Al	5.5
Cr	9.4	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

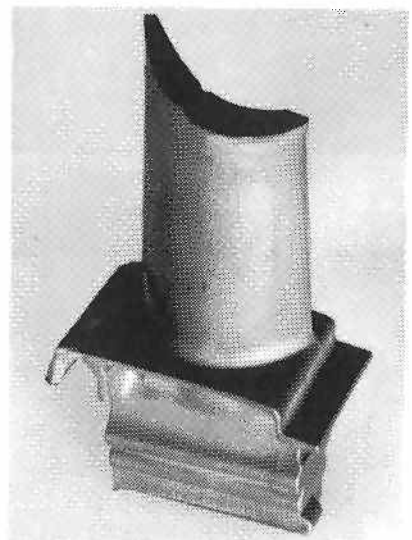
Density-0.308 lbs/cu.in.
(8.54 gms/cc)

Figure 4.

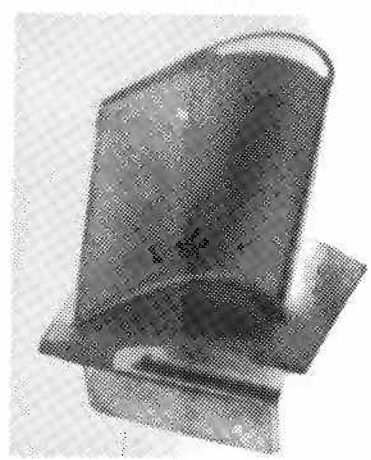
The derivation of several single crystal compositions from MAR M 247 (Fig. 4) was pioneered in the Garrett/NASA MATE program which commenced in 1977 (7, 31). The two alloys studied extensively were NASAIR 100 and NASAIR Alloy 3 (contains a minor Hf addition).

CMSX-2 and CMSX-3 single crystal superalloys, developed in 1979, are both derivatives of the MAR M 247 composition. These alloys are proving to have good castability and solutioning characteristics and an attractive combination of mechanical and environmental properties for turbine blade (Fig. 5) and vane airfoil components (8). CMSX-4 is a Re containing third generation, ultra high strength single crystal superalloy developed for small gas turbines, where dimensional constraints limit cooling configurations (9).

CM 247 LC, developed in 1978, is a chemistry modified superalloy derived from the MAR M 247 composition, specifically designed for DS turbine blade and vane segment applications (10). The alloy demonstrates exceptional resistance to grain boundary cracking during DS casting of advanced complex cored, thin wall airfoils. The advent of production vacuum heat treatment furnaces with close control of temperature developed for the narrow solution heat treatment range of some single crystal alloys facilitate, in conjunction with prehomogenization step heat treatments, solutioning of DS CM 247 LC at temperatures up to 2300°F (1260°C) without incipient melting. This heat treatment results in complete solutioning of the γ', with appreciable solutioning of the γ - γ' eutectic, which enhances creep and tensile property response of the alloy (11). DS CM 247 LC commenced turbine engine flight service in 1985. The alloy has also proved to be suitable for the fine grain casting processes developed for integral cast wheels for small turbine engines (12).



(i) CMSX-2 Single Crystal, Thin Wall, Complex Cored Turbine Blade.



(ii) CMSX-2 Single Crystal, 1st Stage Turbine Blade - Advanced TM 333 Engine (24). Courtesy: Turbomeca S.A.

Figure 5.

CM 186 LC is a Re containing derivative of CM 247 LC with creep properties in between CMSX-2/3 and CMSX-4 (36). The alloy also does not contain V, which is deleterious to environmental properties, and demonstrates an approximate 20°F (11°C) stress-rupture temperature capability improvement over DS René 150 (13). Turbine engine testing with complex cooled 1st stage DS CM 186 LC turbine blades is in progress in an advanced 2600°F (1427°C) inlet temperature small turbine engine.

CMSX SINGLE CRYSTAL ALLOYS

Development Concepts

CMSX-2, developed using a multi-dimensional approach, achieves a high level of balanced properties as shown in Figure 6. This is in contrast to other approaches such as the restricted two dimensional approach utilized by Yamazaki et al (14, 15).

CMSX-2 Alloy Development Goal

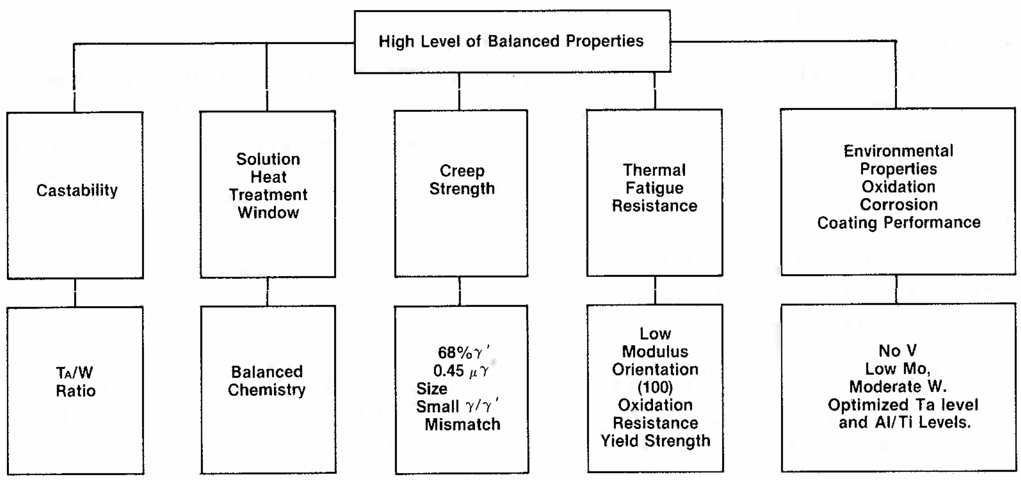


Figure 6.

The chemistry modifications applied to MAR M 247 to develop CMSX-2 (nominal composition shown in Fig. 7) are summarized below with respect to function and objectives:

- Grain boundary strengthening elements (B, Hf, Zr and C) are removed to achieve a very high incipient melting temperature [2435°F (1335°C)].

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-0.309 lbs./cu.in. (8.56 kg./dm³)

Figure 7.

- Partial substitution of Ta for W (CMSX-2 has 6% Ta) to give good single crystal castability, high γ' volume fraction (68%) (22), improved γ' precipitate strength, microstructural stability (freedom from α W and W, Mo rich μ phases), good oxidation resistance and coating stability.
- Co is maintained in the alloy to increase solid solubility / microstructural stability.
- Chemistry balance (16) is designed to ensure a wide and practical solution heat treatment temperature range or "window" (difference between the γ' solvus and the incipient melting temperature) of at least 40°F (22.2°C) (8).
- Phacomp control of the alloy's chemistry avoids occurrence of the deleterious σ phase.

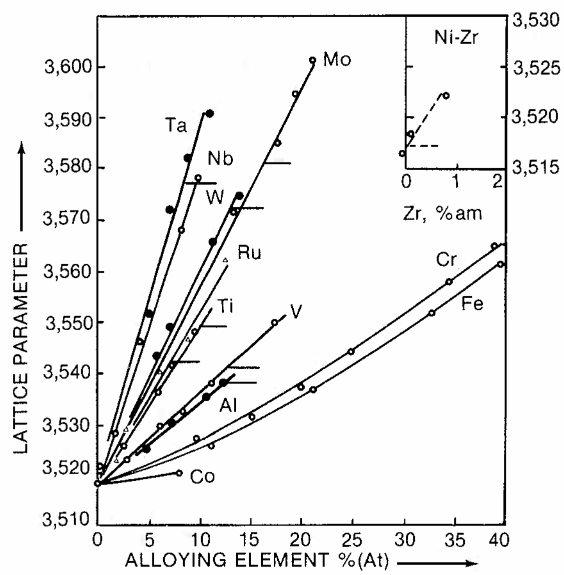


Figure 8. Influence of Alloying Elements on Lattice Parameter of Binary Nickel Alloys. Source: Kornilov. (17)

Figure 8 (17) shows the relative potency of Ta, W and Mo as solid solution strengtheners in binary Ni alloys - Ta being the most powerful strengthener on an atomic percent basis. Ta also partitions strongly to the γ' phase, increasing the volume fraction and also stiffening the γ' due to its relatively large atomic size. The strength of the γ' phase is important since dislocation movement by bypassing γ' particles is more difficult than cutting the γ' and thus a high γ' strength microstructure provides greater creep resistance.

Detailed transmission electron microscopy (TEM) studies (18) of dislocation movement in cast high strength superalloys, such as MAR M 002 and its single crystal derivatives, show it is important to ensure that the antiphase boundary (APB) energy is high, so the stacking fault mode of creep deformation occurs at temperatures up to 1562°F (850°C), thus ensuring high creep strength. It is observed that tantalum additions raise the APB energy relative to the stacking fault energy (18), leading to the increased tendency for stacking faults to be formed at lower temperatures.

Castability

The CMSX alloys are designed to provide good foundry performance since castability is a crucial alloy performance criteria for any complex, thin-walled turbine blade or vane component -- a characteristic often given limited attention in alloy design. It not only affects the yield and cost of components but also the defect level and, hence, component performance. Single crystal casting defects of concern are:

- "Freckling" (spiral of equiaxed grains due to elemental segregation in the liquid state)
- Microporosity
- Spurious grains/"slivers"
- Stable oxide inclusions
- Carbides

The partial substitution of Ta for W in CMSX-2 alloy, compared to the MAR M 247 chemistry, assists with overcoming the "freckling" problems inherent with the low Ta, high W single crystal alloys. European work with single crystal, shrouded, solid blade castings has shown NASAIR 100 (10.5% W, 3.3% Ta) (7, 31) to be "freckle" prone. Increasing the Ta content (reduced W/Ta ratio) reduces the "freckling" tendency of given alloys due to their compositional balance. The partial substitution of Ta for W in CMSX-2 makes the alloy dramatically less prone to "freckling" defects when cast into complex configuration single crystal parts. Casting configuration is important since a crucial factor controlling "freckle" formation is the depth and shape of the "mushy region" during solidification or the temperature gradient and its uniformity in this region (19).

Extensive worldwide experience over the last 6 years with 12 different single crystal casting processes has shown CMSX-2 can be readily cast into a variety of complex single crystal turbine blade and vane parts, utilizing moderate to high thermal gradients. "Freckling" problems can occur with low thermal gradient processes. The lower Ta, higher W alloys, such as NASAIR 100 (7, 31) and SRR 99 (18), can only be readily cast using the small chill plate [6" (150 mm) dia.], high thermal gradient process [18 (p. 119), 20].

Producibility

Firm aim chemistry and specification ranges are established for CMSX-2 and CMSX-3 alloys (nominal composition shown in Fig. 9) utilizing extensive evaluation and performance data from 18 heats of CMSX-2 [including three production 8000 lb. (3630 kg) heats] and 17 heats of CMSX-3 [including two production 8000 lb. (3630

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-0.309 lbs./cu.in.
(8.56 kg./dm^3)

Figure 9.

kg) heats]. C, S, [N] and [O] data from the production heats are shown in Figure 10, along with data from a small developmental 50% revert/50% virgin heat. Several studies undertaken in the U.S. and Europe confirm high [N] and [O] levels in single crystal superalloy ingot adversely affect SX casting grain yield, supporting the importance for low [N] and [O] levels in the master alloy. C, S, [N] and [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 (21).

CMSX-2 & CMSX-3 8000 lb. (3630 kg.)
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-2	V6821	16	2	3	1
CMSX-2	VF615*	14	8	2	1
CMSX-3	V6670	24	6	4	2
CMSX-3	V7089	28	5	2	1

* 250 lb 50% Virgin/50% Foundry Revert Heat

Figure 10.

CMSX-3 alloy, which is CMSX-2 with .1% Hf originally added for improved aluminide coating performance, has essentially the same properties as CMSX-2, including coating performance, which is excellent for both alloys (10).

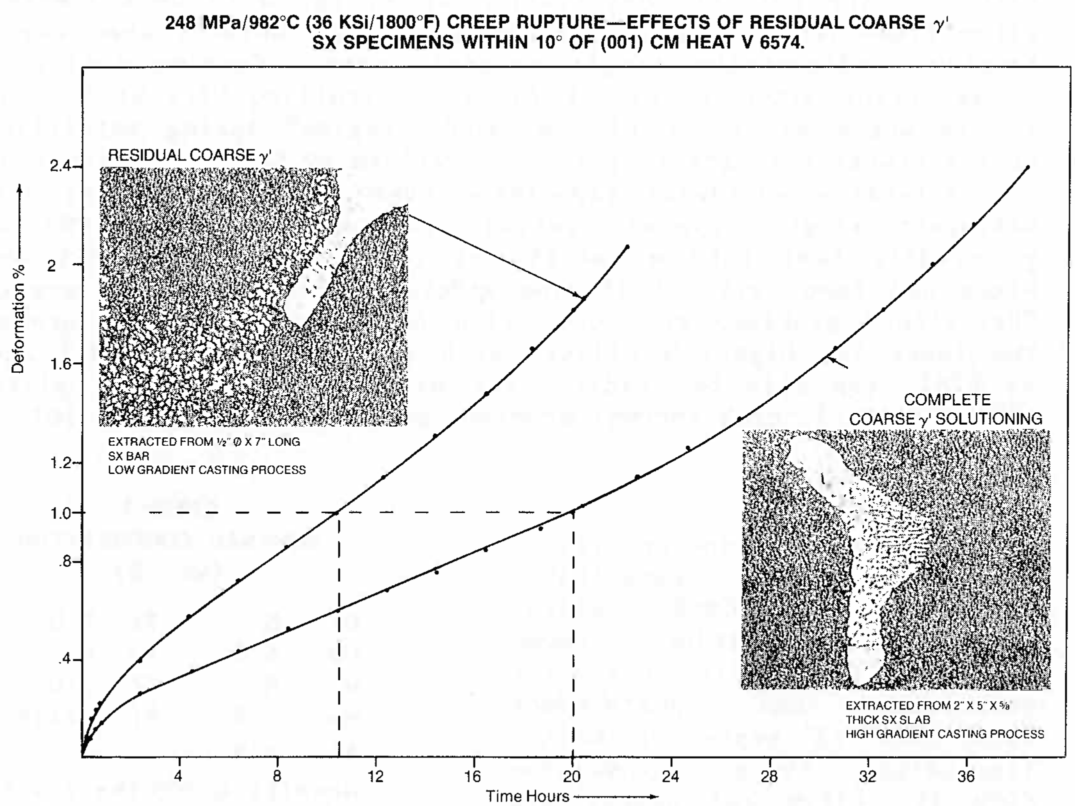


Figure 11.

CMSX-4 alloy (9), which is an ultra-high strength Re-containing derivative of CMSX-2 alloy, demonstrates similar castability and environmental properties to CMSX-2. The maximum heat size produced to date in CMSX-4 is 250 lbs (113 kgs).

Heat Treatment

Solutioning. It is important to achieve a fully solutioned γ' microstructure in single crystal superalloy components. Figure 11 shows that residual coarse γ' in the microstructure (cast using a low thermal gradient process) almost halves the time to 1.0% creep at 36 ksi/1800°F (248 MPa/982°C), compared to a fully solutioned γ' microstructure [cast using a high thermal gradient process (20)] from the same heat.

CMSX-2/3, by nature of their wide [approximately 50°F (28°C)] solution heat treatment "windows", are straightforward to fully solution the γ' and much of the γ - γ' eutectic without incipient melting, using available production vacuum heat treatment furnaces which are qualified for single crystal casting solution treatment.

Chemical Composition of the γ' Phase in CMSX-2 (Wt. %) (Ref. 22)

Ni	69.25
Co	3.15
Cr	2.05
Mo	0.30
W	7.25
Al	7.55
Ti	1.30
Ta	9.15

Figure 12.

Aging. The weight fraction of γ' in CMSX-2 is approximately 68% with chemistry as shown in Figure 12 (22), both being independent of the aging treatments used. The measured lattice parameter of the γ' is 3.5865 Å (22), with a γ / γ' misfit at room temperature of + 0.14% (22) and - 0.33% at 1922°F (1050°C) (23).

It is reported by ONERA (22, 24) that a high temperature aging heat treatment (T_2) [16 hrs./1922°F (1050°C) AC] following solution treatment, with subsequent intermediate temperature aging [20 hrs./1600°F (871°C) or 48 hrs./1562°F (850°C)], gives CMSX-2 cuboidal γ' with a mean size of 0.45 µm which optimizes creep response. Similar γ' morphology

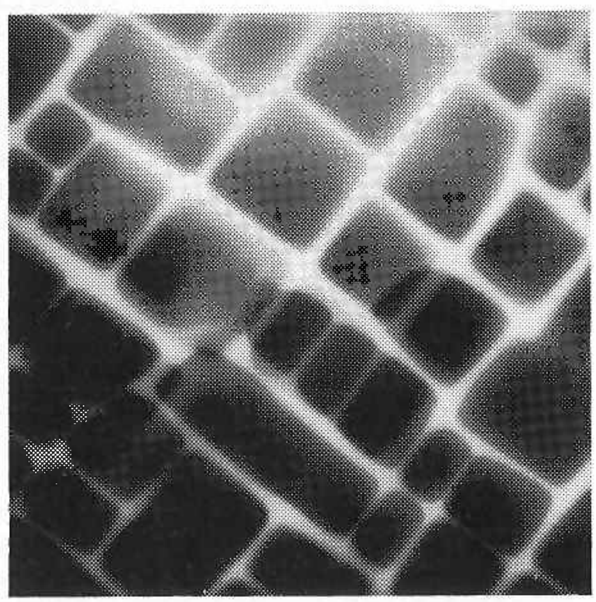


Figure 13. Morphology of γ' Precipitates in CMSX-2 Alloy After T_2 Heat Treatment (24).

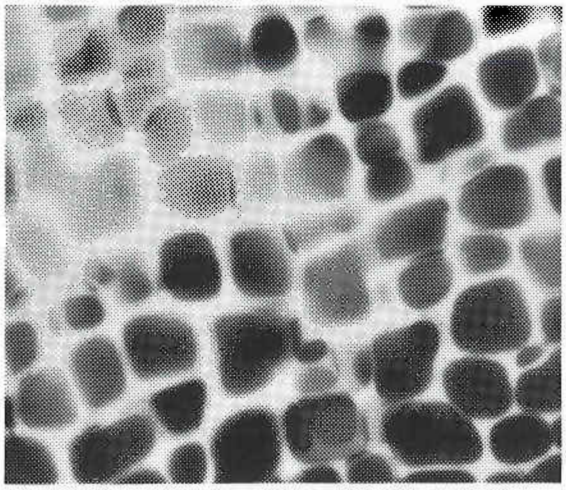


Figure 14. Morphology of γ' Precipitates in CMSX-2 Alloy After T_1 Heat Treatment (24).

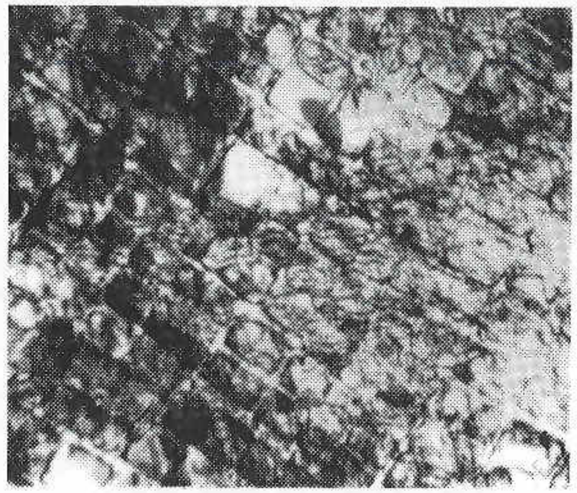


Figure 15. Homogeneous Deformation in CMSX-2 (Treatment T_2) After 0.16% Creep Strain at 760°C (T.E.M. Micrograph) (24).

and size is obtained with a 4 hr./1975°F (1079°C) AC post solution treatment. The morphology of the γ' in CMSX-2 with this ONERA type aging treatment is shown in Figure 13 (24) compared to the conventional irregular shaped γ' particles with a mean size of 0.3 µm, resulting from a 5 hrs./1800°F (982°C) AC + 48 hrs./1562°F (850°C) aging (T_1) (Fig. 14) (24). T_2 type specimens at 1400°F (760°C) deform in a homogeneous manner right from the early stage of creep (Fig. 15). The homogeneous nature of the deformation leads to a rapid strain hardening of the material, causing a decrease in the creep rate. The T_1 heat treatment which produces smaller and odd-shaped particles favors inhomogeneous deformation within the specimen due to the precipitate shearing during the early stages of creep (Fig. 16). In this case, the amplitude of primary creep is high, and the strain hardening of the material is achieved at a much later stage compared with that of the T_2-type heat treated specimens.

During creep at high temperature, the γ' precipitates coarsen in the form of rafts perpendicular to the stress axis. The kinetics of raft formation depends, among other

Figure 16. Inhomogeneous Deformation in CMSX-2 (Treatment T_1) During Primary Creep at 760°C (T.E.M. Micrograph) (24).

factors, upon the testing temperature. At 1922°F (1050°C) under a stress of 17.4 ksi (120 MPa), the rafts form within a few hours (Fig. 17); the rafts have a high aspect ratio in the T_2-type heat treated specimens in which the cuboidal γ' precipitates are already aligned. The lateral extension of the γ' phase in the form of rafts causes the specimen to creep at a much lower rate compared with the creep rate of the material in which the γ' phase coalesces in an irregular manner. CMSX-2 & 3 alloys showing this type of rafted γ' morphology possess very long rupture lives at high temperatures. In these alloys, the misfit between the γ and γ' phases is found to be negative at high temperatures (25).

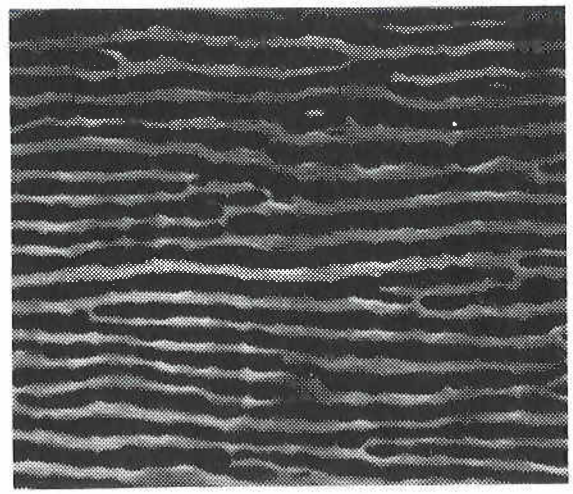


Figure 17. Oriented Coalescence of the γ' Phase in CMSX-2 After 20 Hours of Creep at 1050°C Under 120 MPa (Tensile Stress Axis is [001]) (24).

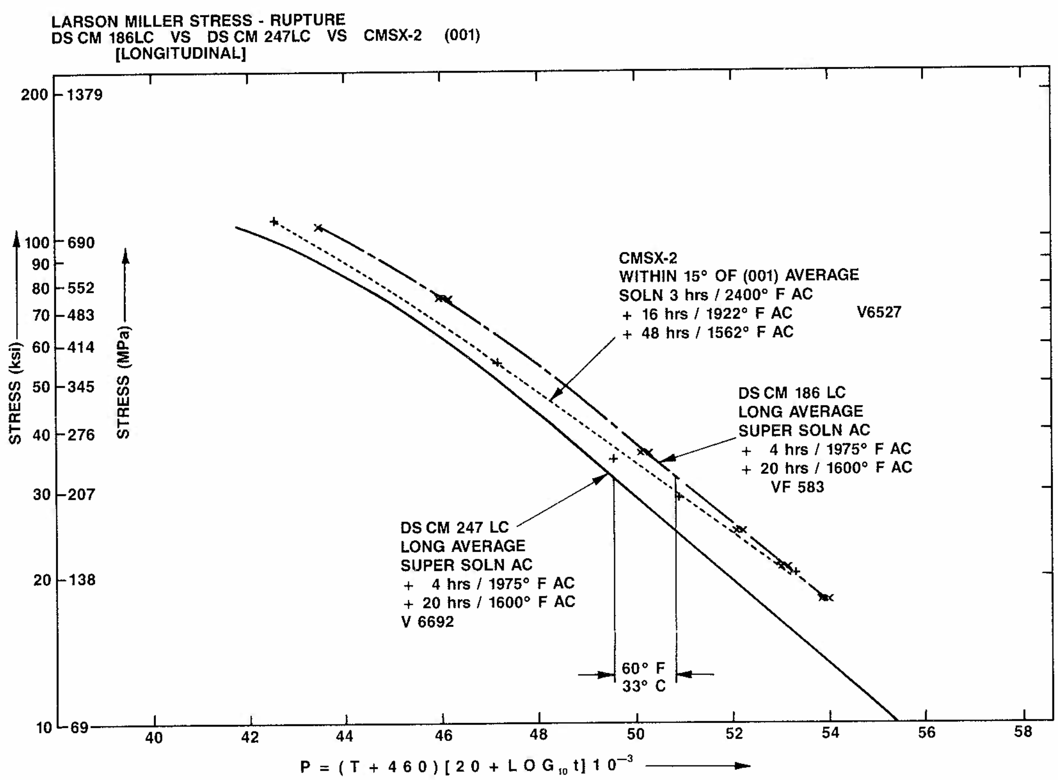


Figure 18.

Mechanical Properties

Stress- and Creep-Rupture. Figure 18 shows a Larson-Miller plot of CMSX-2 (001) vs DS CM 247 LC (super solutioned - longitudinal) stress-rupture properties where it is apparent that the temperature capability advantage increases with increasing temperature/decreasing stress - at typical blade airfoil stress levels [20 ksi (138 MPa)] (26), the capability advantage of CMSX-2 is 57°F (32°C). Degradation of stress-rupture properties with thin wall specimens [.020"/.030" (.5 mm/.75 mm thick)] with CMSX-2 & 3 has been observed (27, 26), probably due to oxidation effects, particularly at high temperatures. This is very much less than experienced with equiaxed specimens in MAR M 247 (32) due to oxidation of the transverse grain boundaries. Creep properties (Fig. 19) (time to 1%), which is more pertinent from a blade design viewpoint, is less affected by section thickness (26) as the amount of oxidation before attainment of 1% creep strain is essentially negligible.

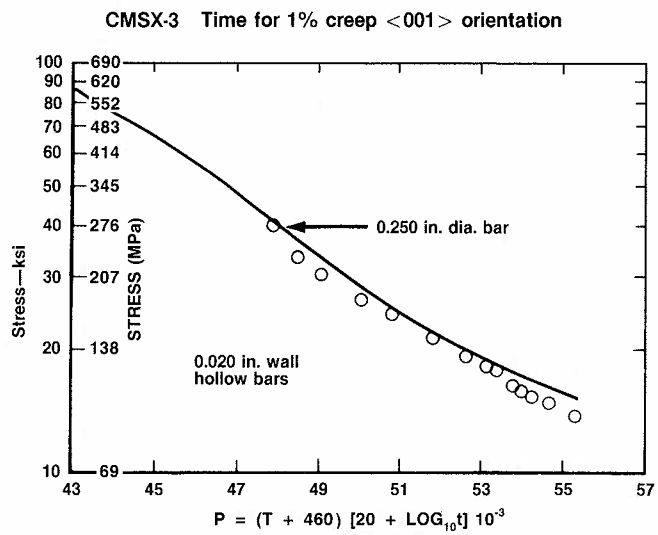


Figure 19. Thin-wall (0.020") creep properties of the CMSX-3 alloy. The solid line describes data obtained on 0.250" diameter bars (26).

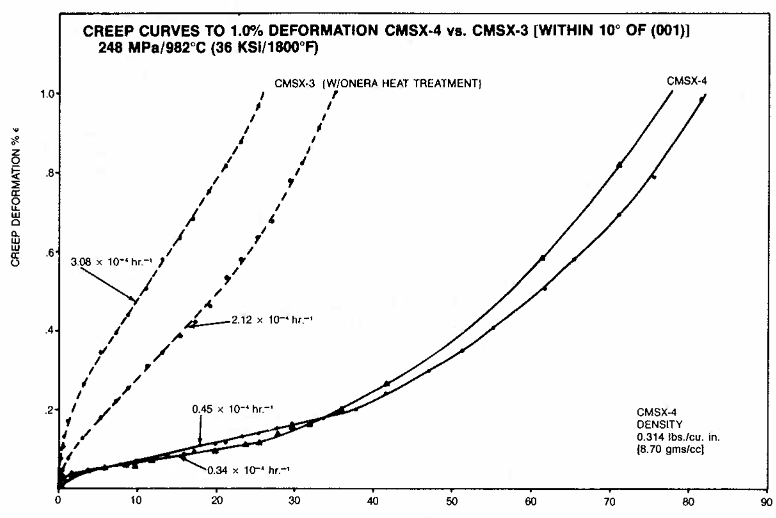


Figure 20.

The primary and secondary creep rates for CMSX-4 are much less compared to CMSX-2 & 3, with a temperature capability advantage of 45°F (25°C) apparent based on time to 1% creep at 36 ksi/1800°F (248 MPa/982°C) [Fig. 20 (9)]. The Re in CMSX-4 is shown to retard the growth of the γ' during creep testing (30).

Fatigue. An important property which must be considered while selecting single crystal superalloys for turbine blade applications is the fatigue strength. Single crystals of CMSX-2 were cast both under low and high gradient conditions and then subjected to the high cycle fatigue (HCF) tests in the repeated tension mode at 1598°F (870°C) (24); the results are reported in Figure 21 (24). The fatigue resistance of specimens cast under very high temperature gradient (laboratory conditions) is much superior to that of the material cast under industrial conditions, primarily due to the very small pore size (< 10 μm) inherent in the high gradient specimens. The single crystals cast under industrial conditions have a more heterogeneous structure where the interdendritic spacing and the level of porosity vary along the length of the bar. Specimens corresponding to the beginning of solidification show a better fatigue resistance compared with those corresponding to the end of the solidification process. Some fatigue tests were also performed on specimens in which a rafted γ' morphology was developed prior to testing. It is interesting to note that the fatigue behavior is not significantly affected by the rafted γ' morphology (24).

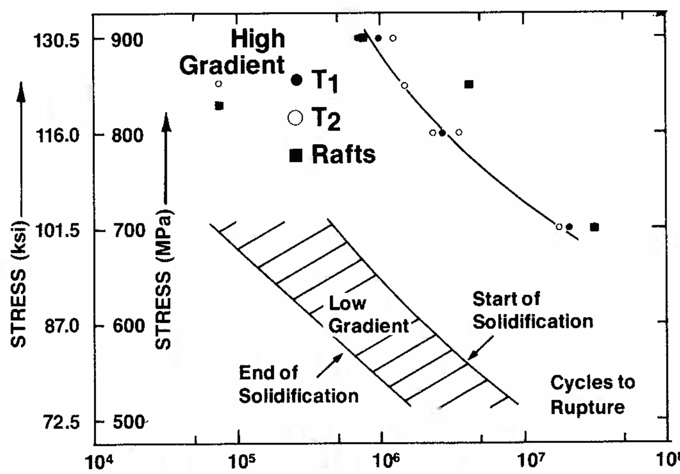


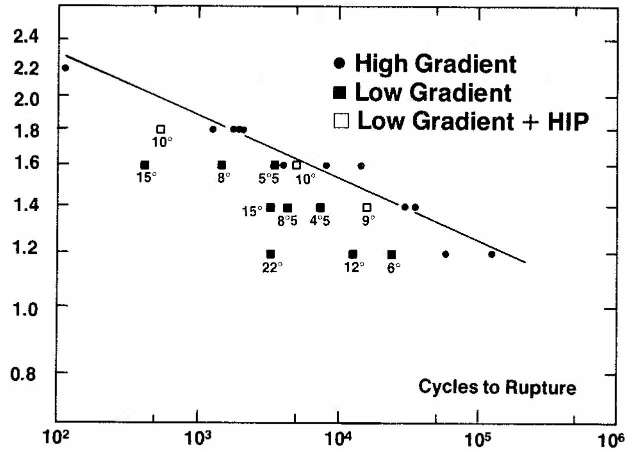
Figure 21. Effect of Thermal Gradient and Heat Treatments on the H.C.F. Behavior of CMSX-2 at 1598°F (870°C) (f=50 Hz) (24).

Strain-controlled fully reversed low cycle fatigue (LCF) tests performed at 1400°F (760°C) confirm the much better fatigue behavior of single crystals cast under high gradient (Fig. 22) (24). In this type of test, the higher the deviation from the [001] orientation, the shorter the fatigue life. It can be seen in Figure 22 that for a total strain range of 1.2%, the fatigue life is decreased by an order of magnitude when the crystal orientation, relative to the [001], moves away from 6 to 22°. The decrease in fatigue life is a consequence of the increase in stress level through the increase of elastic modulus. Since the plastic strain component at 1400°F

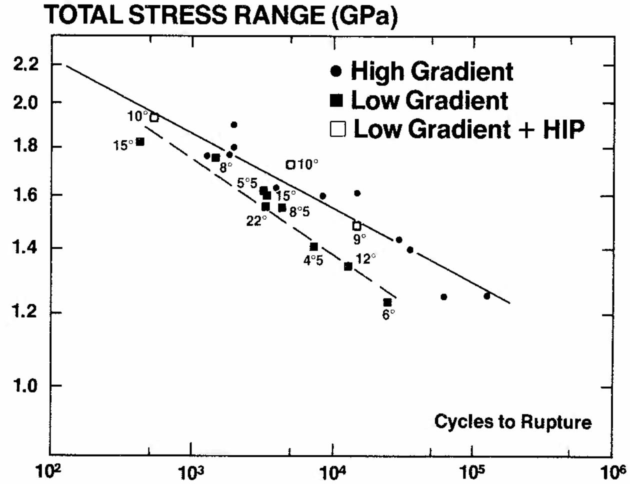
(760°C) is small, the results can be plotted as total stress vs. number of cycles to failure (Fig. 22) (24). In this representation, the effect of crystalline orientations on the fatigue life of the industrially processed single crystals is not apparent, and all the results of low gradient single crystals can be represented by a single curve.

The examination of fracture surfaces shows that the cracks are initiated at microporosity, which shows that these "defects" (microporosity) are of prime importance in determining the fatigue life of CMSX-2. The size of microporosity in "industrial" single crystals can be as large as 50 to 80 μm but hardly over 10 μm in single crystals cast under very high temperature gradients (laboratory conditions). The adverse effect of microporosity is also confirmed by the results obtained after HIP'ing [1000 bars/2400°F (1315°C)] single crystal bars solidified under the low temperature gradient. The fatigue strength of single crystals cast under low gradients after HIP'ing can be improved after HIP'ing to that of the high gradient processed specimens (Fig. 22) (24).

Isothermal fatigue testing at 1652°F (900°C) compares CMSX-2, DS CM 247 LC and equiaxed MAR



a) Total Strain Range vs. Number of Cycles to Failure



b) Total Stress Range vs. Number of Cycles to Failure

Figure 22. Effect of thermal gradient, orientation and HIP on the strain controlled L.C.F. behavior of CMSX-2 (fully reversed, F=0.33 Hz) at 1400°F (760°C). The numbers represent the deviation, in degrees, from the [001] orientation (24).

M 247 using several different waveforms (28). Under the designated PP waveform in which no creep strain is caused in the fatigue cycle, CMSX-2 [(001) orientation (within 12°)] single crystal, tubular specimens show more than twice the life compared to DS CM 247 LC (longitudinal) and eight times improvement over equiaxed MAR M 247. With several different waveforms where creep strain occurs during the fatigue cycle, the superiority of the single crystal CMSX-2 specimens is not as marked as with the PP waveform; however, the single crystal material still demonstrates longer life than the DS alloy. This comparison is made under high strain rate ($\Delta\varepsilon$ = 1.0%) conditions.

Oxidation & Corrosion Behavior. Turbine engine experience with single crystal blades has shown that environmental resistance is a crucial factor in achieving improved component life cycle costs. In high performance aircraft turbine engines, bare tip oxidation of blades at temperatures > 1900°F (1038°C) and coating durability are of premier concern. Studies to optimize single crystal superalloy/coating combinations are discussed in (29).

The dynamic oxidation behavior of single crystal superalloys CMSX-2 and CMSX-3 at 2075°F (1135°C) has been compared with that of conventional superalloys such as IN 738 LC, René 80 and DS MAR M 200 Hf using the following test conditions: burner rig oxidation testing; T = 2075°F (1135°C); gas velocity = Mach 1; one hour thermal cycle followed by rapid cooling. As shown in Figure 23, the metal loss per side is ten times smaller for CMSX-2/3 in 250 hours compared with that of DS MAR M 200 Hf. Both the microstructural and compositional differences, grain boundaries, carbides and microsegregation are considered to explain the difference in oxidation behavior.

The attractive coating performance of CMSX-2 & 3 alloys is shown in Figure 24. The bare corrosion performance, which is not too far removed from IN792 alloy, is shown in Figure 25.

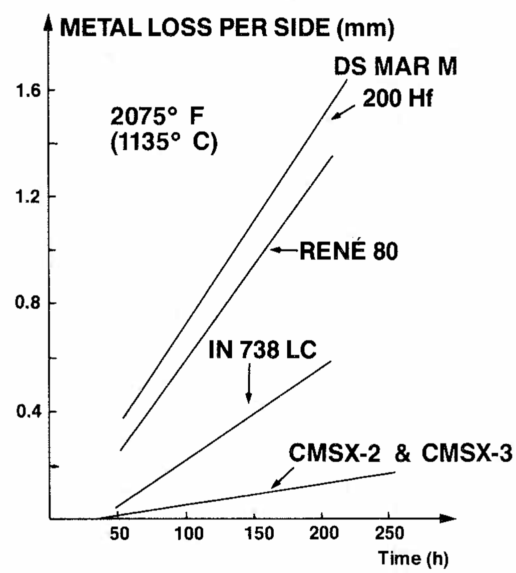


Figure 23. Oxidation Behavior of Various Conventional and Single Crystal Superalloys (Gas Velocity Mach 1, Thermal Cycles of One Hour, Followed by Rapid Cooling).

CM 247 LC & CM 186 LC DS & INTEGRAL WHEEL ALLOYS

DS components have applications in advanced turbine engines in spite of the growth of single crystal technology. Examples are long shrouded blades and vane segments which can be

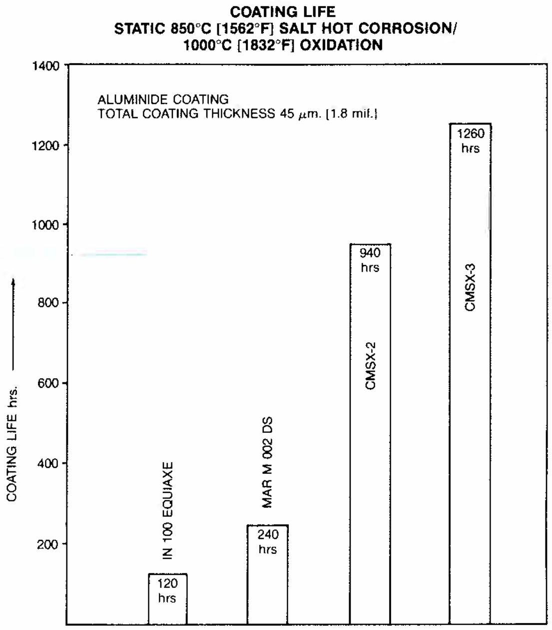


Figure 24.

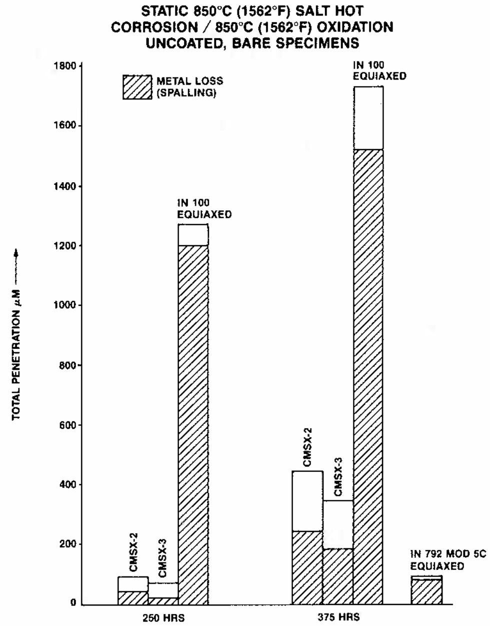


Figure 25.

extremely expensive to produce as single crystal castings. A small turbine engine producer estimates a 90°F (50°C) cooling configuration advantage can be gained with DS blades of a particular configuration, compared to the producable single crystal alternative. This is because a less complex core has to be used with the single crystal castings to avoid recrystallization problems on subsequent solution treatment, due to excessive residual casting stresses.

CM 247 LC (Fig. 26) has been successfully developed from the MAR M 247 composition specifically for DS casting complex, thin-wall blade and vane components. The alloy has exceptional DS castability and ductility (10) and can be readily fully solutioned to improve the creep-rupture and tensile properties (11). The practicality of adhering to the tight chemistry specification requirements for CM 247 LC is apparent in Figure 27, where critical chemistries are shown for six 8000 lb. (3630 kg.) production heats of the alloy.

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 26.

Critical Chemistries DS CM 247 LC
8000 lb. (3630 kg.) 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
V6769	.020	.69	.007	.071	3	3	2
V6876	.018	.71	.005	.070	5	2	1
V6943	.019	.69	.008	.071	7	2	2
V7117	.018	.68	.006	.070	7	2	1

Figure 27.

DS (Long) & SX (001) Alloy 36.0 ksi/1800°F (248.2 MPa/982°C)
Average Creep Data Comparison

Alloy	Hrs. to Creep 1.0%	Hrs. to Creep 2.0%	Rupture Time Hrs.	El. % (4D)
DS CM 247 LC	7.5	16.0	42.0	28.9
DS CM 186 LC	46.2	78.8	167.0	27.2
CMSX-2	26.7	38.5	74.0	33.0
CMSX-4	73.0	97.2	183.7	21.0

Figure 28.

CM 186 LC is a Re containing derivative of CM 247 LC. In recent development studies the alloy demonstrates good DS castability in between MAR M 247 and CM 247 LC (36). Several molds of "difficult" cored blades have been cast without any DS grain boundary cracking problems. CM 186 LC also appears on initial studies to exhibit intrinsic fine, narrow columnar grains on DS casting. The DS longitudinal creep-rupture strength properties of CM 186 LC in the fully solutioned condition lie in between CMSX-2 and CMSX-4 (Figs. 18 & 28). The stress-rupture temperature capability advantage of DS CM 186 LC over DS CM 247 LC is 60°F (33°C) at 36 ksi (248 MPa) conditions and 20°F (11°C) over DS René 150, again at the 36 ksi (248 MPa) stress. Environmental properties of CM 186 LC are expected to be similar to MAR M 247 and CM 247 LC.

CM 247 LC has also demonstrated suitability for the fine grained integral wheel casting processes developed over recent years because of the alloy's castability, ductility and microstructural features (12). At 1400°F (760°C), a typical rim operating condition, CM 247 LC shows half the crack growth rate of similarly fine grain processed MAR M 247 alloy.

CM 247 LC (.07% C) is more conducive to achieving fine, relatively blocky carbide size and shape control in the ingot stock, with carry-over potential to the wheel castings, compared to MAR M 247 alloy (.15% C). Carbide size and morphology have been shown to be important in optimizing LCF and crack growth rate response in integral wheel castings (33, 34). Heavy script-like carbide colonies can nucleate fatigue cracks and act as relatively easy crack paths.

CM 247 LC entered production in April 1986 for integral cast wheels for a small turbine engine. The CM 186 LC alloy warrants consideration for high creep strength integral cast wheels, particularly with some recent process developments where DS airfoils can be cast integrally with fine grained hubs.

SUMMARY AND CONCLUSIONS

With the support and encouragement of the aero gas turbine industry, a family of single crystal, DS blade, vane and integral cast wheel superalloys has been successfully developed from the MAR M 247 composition for turbine engine applications. The alloys in current production, CMSX-2, CMSX-3 and CM 247 LC have been scaled-up to 8000 lb. (3630 kg.) heats and have been evaluated by 12 turbine companies worldwide, up to and including flight turbine engine testing. The alloys are characterized by good castability, solution treatment capability, high strength and oxidation resistance.

The newer alloys, CMSX-4 and CM 186 LC, are undergoing development evaluation, with turbine engine testing scheduled for 1987.

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