

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 super-alloy 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

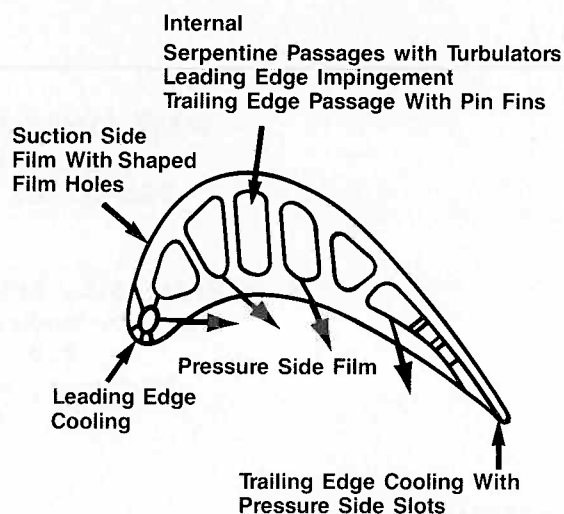


Figure 1. Turbine rotor blade cooling uses such features as shaped holes, turbulators, pin fins and other techniques.

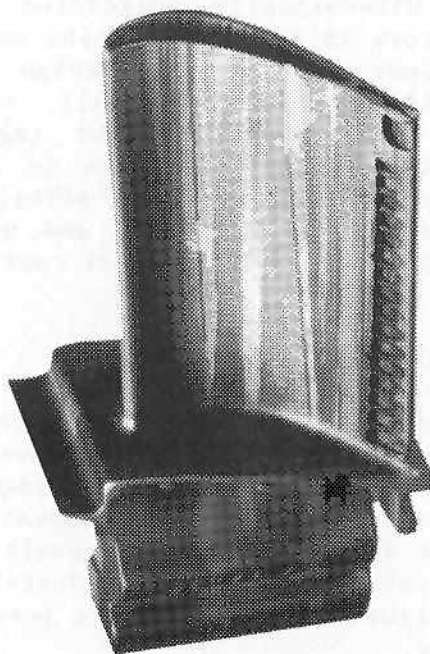


Figure 2. DS Turbine Blade CM 247 LC.

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 $\gamma - \gamma'$ 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 (V_f)
Fine γ' at a fixed total amount of fine & coarse γ'
- DS MAR M 200 Hf Alloy (5)**

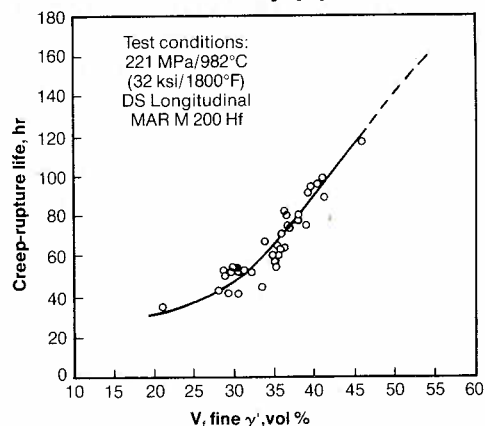


Figure 3.

**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

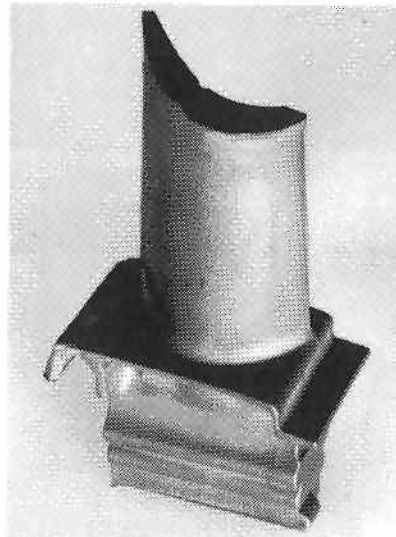
Density-0.308 lbs/cu.in.
(8.54 gms/cc)

Figure 4.

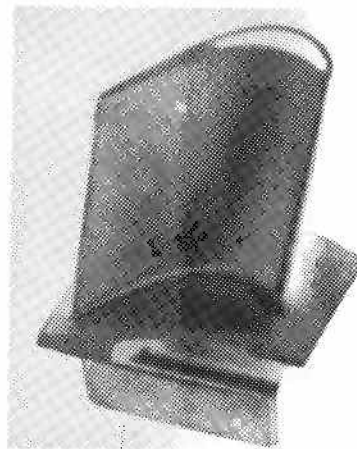
The derivation of several single crystal compositions from MAR M 247 (Fig. 4) was pioneered in the Garrett/NASA MATE program which commenced in 1977 (7, 31). The two alloys studied extensively were NASAIR 100 and NASAIR Alloy 3 (contains a minor Hf addition).

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 $\gamma - \gamma'$ 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).

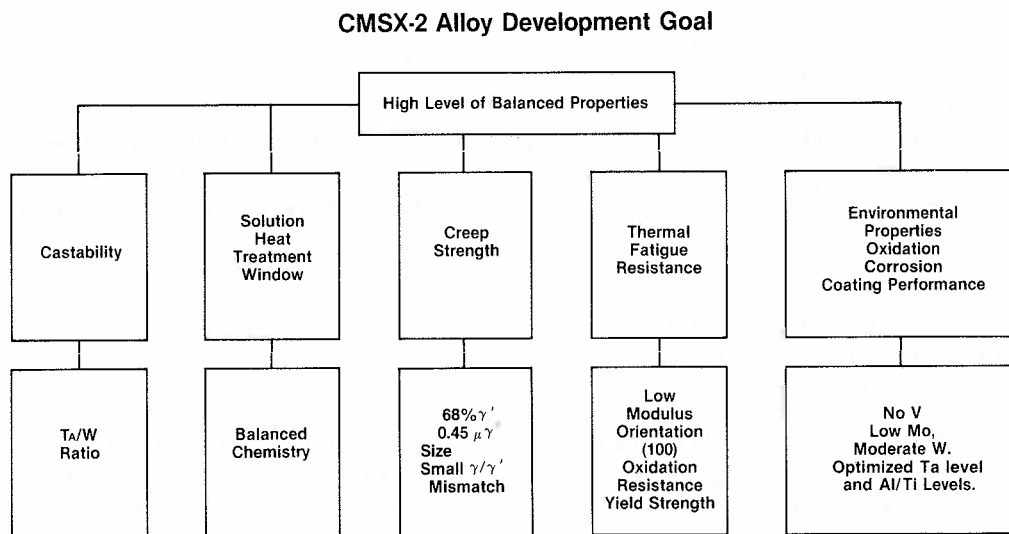


Figure 6.

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.

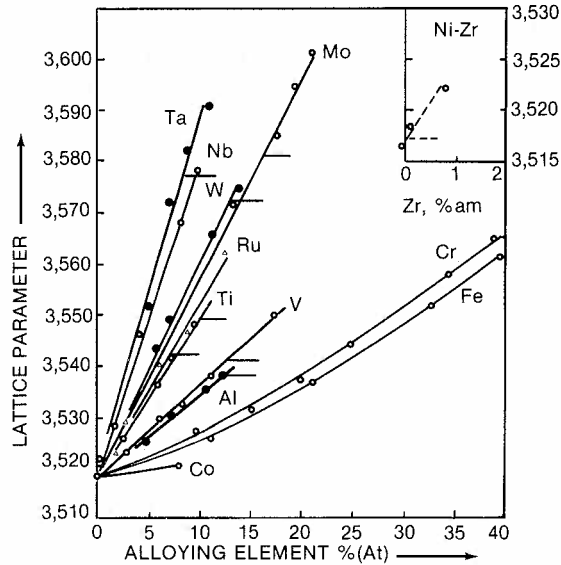


Figure 8. Influence of Alloying Elements on Lattice Parameter of Binary Nickel Alloys. Source: Kornilov. (17)

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./dm³)

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-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).

**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.

**248 MPa/982°C (36 KSI/1800°F) CREEP RUPTURE—EFFECTS OF RESIDUAL COARSE γ'
SX SPECIMENS WITHIN 10° OF (001) CM HEAT V 6574.**

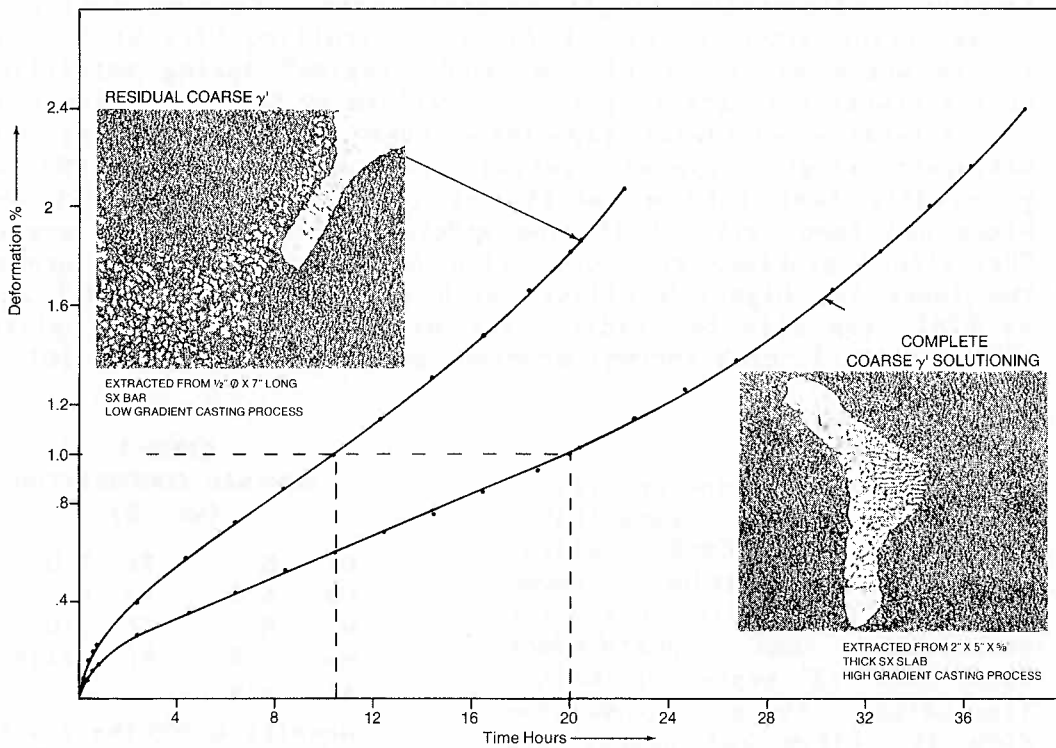


Figure 11.

