New Alloy Developments in Single Crystal and DS Alloys

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1. INTRODUCTION

In the 1940's and early 1950's, superalloy development was conducted primarily by the International Nickel Company, either in the USA where the popular IN 713 C and IN 718 alloy were developed or in the UK where the Nimonic series of alloys were developed. By the mid 1950's, a number of entrepreneurs entered the alloy development field led by such people as Rudy Theilmann (Sierra alloys, MAR M 200), Roger Wandel (Waimet alloys, WI-52) and James French Baldwin (B 900, Sorcery alloys). By the 1960's, other larger organizations entered into superalloy development, including GE (René alloys – Ross, Wukusick), TRW (Collins-Quigg) and Martin Marietta (Lund, Danesi, Hockin, Wheaton). It is interesting to note that today's most advanced equiaxed superalloys (MAR M 247 and MAR M 509) were developed by Martin in the late 1960's and early 1970's. A belief that melting point constraint restricted further advancement in alloy development caused emphasis to be directed toward process improvement. The development of casting concepts to produce airfoils with grain aligned structure (DS) and later single crystals changed the alloying concepts utilized.

Since DS was developed by Pratt and Whitney, patented and used, at least initially, solely by Pratt, DS alloy design was controlled by them. They elected to use an existing alloy, MAR M 200, for DS application. Later this alloy was modified with a hafnium addition to create alloy PWA 1422. The first non-Pratt source to use DS castings was General Electric. GE elected to use the standard alloy, René 80, for DS application, later modifying it with hafnium to create alloy Rene 80 H.

Like DS, single crystal airfoil technology was invented and developed by Pratt and Whitney. Here, however, unlike its DS concepts, Pratt developed specific compositions for single crystals. These new compositions were based on concepts developed by Gell Duhl and co-workers /1/ where grain boundary strengthening elements (primarily carbon, zirconium, boron and hafnium) were removed or minimized in the alloy – a logical step since no grain boundaries were present in the casting. The beneficial results of removing the grain boundary strengtheners was that the incipient melting temperature was raised, combined with an increased propensity for using heat treatments, to fully solution the gamma-prime phase with resultant better creep strength.

The pioneer Pratt and Whitney single crystal alloy is alloy 454 or PWA 1480. PWA 1480 is a high tantalum (12%) nickel-base alloy which is based on the common Pratt concept of high aluminum (5.0) low titanium (1.5) (gamma-prime formers). PWA 1480 is quite castable and has good properties, including oxidation resistance; the major disadvantage of PWA 1480 is that it is difficult to solution treat due to a very narrow "heat treatment window". Often, step solution treatments are required to attain adequate solutioning.

Like with DS, GE was the first non-Pratt engine maker to move to single crystal airfoils. GE also used the Gell concepts based on reduced grain boundary strengtheners. Different from Pratt, however, they followed the basic GE alloy concepts (higher titanium, lower aluminum) in developing their basic first generation single crystal alloy, GE René N-4. This alloy is castable and has good hot corrosion resistance. It does, however, have a lower melting point than PWA 1480.

The merits of DS and single crystal airfoils were obvious to other engine makers, and they felt the need to enter this field. Some like Rolls-Royce developed their own alloys (SRR 99 and RR 2000). Others felt the need for more "generic" industry-wide alloys, like the equiaxed low alloys of the 1950's (IN 713 C and IN 718) and Martin's MAR M 247 of the 1970's. With the opening, Cannon-Muskegon attempted to fill this void by developing a series of single crystal alloys (the CMSX® series), and also by developing some DS alloys. These alloys over the past ten years have received wide acceptance. In the following, these alloys are described along with a brief discussion of their origin and some of their basic properties.

2. CANNON-MUSKEGON ALLOYS

A. *Single Crystal Alloys*

As a starting point for developing single crystal alloys, Cannon-Muskegon (Harris and Erickson) started with the basic MAR M 247 composition. This includes the relatively high aluminum (5.6) and low titanium (1.0), a characteristic of most of the "Pratt" type alloys. All C-M single crystal alloys also contain low grain boundary strengthener, as advocated in the "Gell concepts". Thus, the major variables optimized in most Cannon alloys are the solid solution elements: tantalum, tungsten, molybdenum, chromium, cobalt and rhenium /2/.

CMSX-2® and CMSX-3®

The first single crystal alloy developed at Cannon-Muskegon was CMSX-2. The principal element composition of CMSX-2 is shown in Table 1, as compared to PWA 1480 and GE René N-4. What is presented in CMSX-2 is optimized levels of solid solution elements, tantalum, tungsten and molybdenum (6, 8 and 0.6). Chromium is reduced slightly to 8%, increasing strength with a slight penalty in the beneficial corrosion effects of chromium. Cobalt, while reduced to the 5% level, is still considered essential for gamma prime stability.

CMSX-2 has a relatively high melting point (approximately 1335 °C) and a reasonably wide solution heat treatment window (28 °C), such that the alloy can be solutioned with a single step heat treatment. The oxidation resistance of CMSX-2 is very good (see Fig. 1). Mechanical properties are some 35 °C better than standard DS materials and are generally equivalent to PWA 1480 and René N-4 (see Fig. 2).

CMSX-3 is identical to CMSX-2 except that a small hafnium addition (0.1%) is made in CMSX-3. This hafnium addition is reported to provide for better adherence of aluminide coatings. The hafnium addition has the disadvantage of lowering the alloy's melting point by 19 °C. The heat treatment window for CMSX-3 solutioning is still quite wide enabling solutioning to be accomplished with a single step heat treatment, although most users to multi-stage step solution heat treat to eliminate eutectic gamma-prime improving fatigue properties.

CMSX-3 has found most of its end use applications in the USA (Allison and Garrett), while CMSX-2 is used more internationally. Major users of CMSX-2 are IHI in Japan and Turbomeca in France.

CMSX-6®

All commercial single crystal alloys are quite dense. This includes PWA 1480, GE N-4 and CMSX-2. There are, however, a number of rotors which utilize equiaxed blades from low density alloys, like IN 100, which would be benefited by single crystal properties, but which cannot take the high density of standard single crystal alloys. In answer to the problem, Cannon-Muskegon (at the behest of MTU) developed a low density single crystal alloy. This alloy is CMSX-6.

CMSX-6 differs from the other Cannon-Muskegon single crystal alloys in that it has a higher level of titanium (4.8) and considerably lower solid solution (tantalum and tungsten) levels. The composition of CMSX-6 is shown in Table 2.

Table 1

Major Element Compositions of First Generation Single Crystal Alloys

	Ni	Cr	Co	Ta	W	Mo	Cb	Al	Ti
CMSX-2	Bal	8	8	6	8	0.6	-	5.6	1.0
PWA 1480	Bal	10	5	12	4	-	-	5.0	1.5
Rene N-4	Bal	9	8	9	6	2	0.5	3.7	4.2

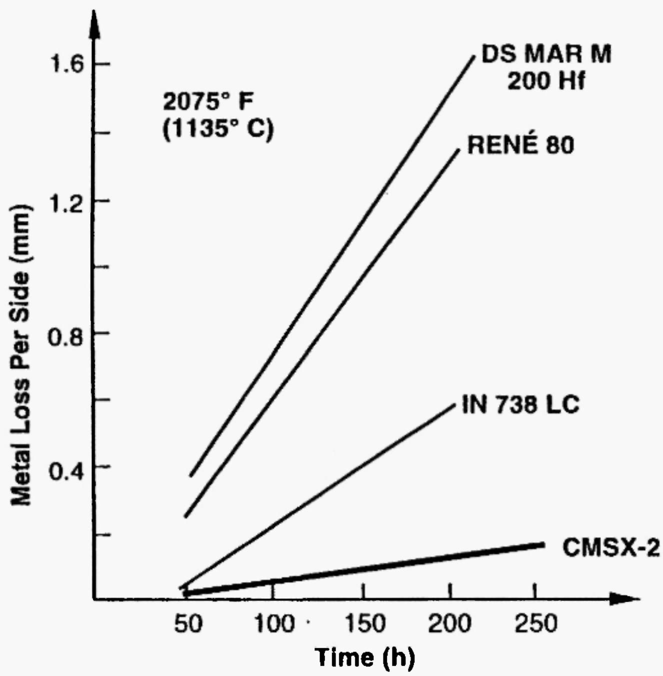

Fig. 1: Oxidation resistance of CMSX-2 compared to other alloys.

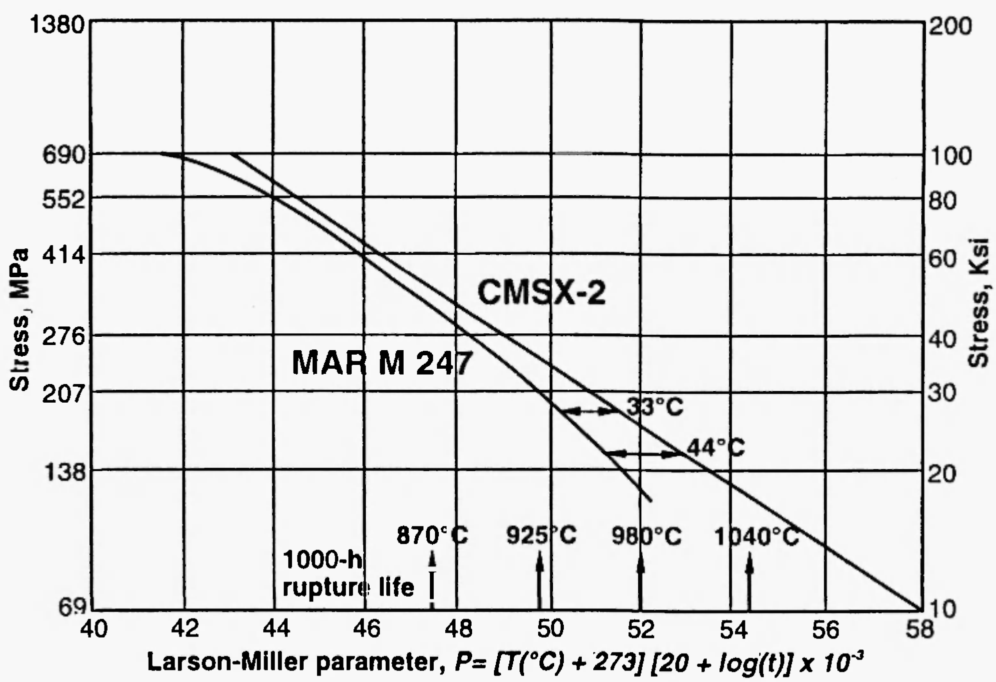

Fig. 2: Stress rupture properties of CMSX-2 compared to MAR M 247.

Table 2

Major Element Composition of CMSX-6®

	Ni	Cr	Co	Ta	W	Mo	Al	Ti
CMSX-6	Bal	10	5	2	-	3	4.8	4.7

The properties of CMSX-6 density corrected are roughly equivalent to CMSX-2, PWA 1480 and René N-4. CMSX-6 is heat treatable. Thus, where density is paramount, CMSX-6 provides a viable single crystal alternative. In this aspect the alloy is unique (the only other low density alloy is RR 2000).

CMSX-4®

CMSX-4 is an advanced second generation single crystal alloy containing rhenium (3%). The composition of CMSX-4 is shown in Table 3. With rhenium and an optimized composition, CMSX-4 exhibits strength properties some 35 °C better than first generation alloys (see Fig. 3). Oxidation and corrosion properties (see Figs. 4 and 5) are also quite good for CMSX-4. The major disadvantage of the alloy is the added cost resulting from the 3% rhenium. CMSX-4 is being widely evaluated worldwide (U.K., Germany, Japan, France and the USA). In most instances, test performance has been outstanding when compared to existing single crystal or DS alloys. Property enhancement has, in general, more than offset the higher cost of the alloy.

B. DS Alloys

As stated previously, process development of the 1960's led to the invention of the grain aligned casting process, specifically directionally solidified (DS) castings. Engine makers other than Pratt and GE first turned to MAR M 247 as a potential DS alloy. This seemed logical particularly in view of the outstanding performance of this alloy as an equiaxed alloy. Unfortunately, MAR M 247 had two characteristics which hampered its use as a DS alloy: (1) it had a tendency to crack on DS casting, particularly with thin walled cored airfoils, and (2) it was difficult to fully solution the gamma-prime without encountering incipient melting.

Cannon-Muskegon, in response to this need, developed the CM 247 LC® alloy. CM 247 LC, a modification of MAR M 247, exhibited little tendency to crack upon DS casting and also proved to be fully solutionable. Thus, CM 247 LC has proven to be an effective DS alloy and has received acceptance worldwide, including GE in the USA, MTU in Germany, and in several applications in Japan. The composition of CM 247 LC is shown in Table 4.

Table 3

Major Element Composition of CMSX-4®

	Ni	Cr	Co	Ta	W	Mo	Al	Ti	Re
CMSX-4	Bal	6.5	10	6	6	0.6	5.6	1.0	3.0

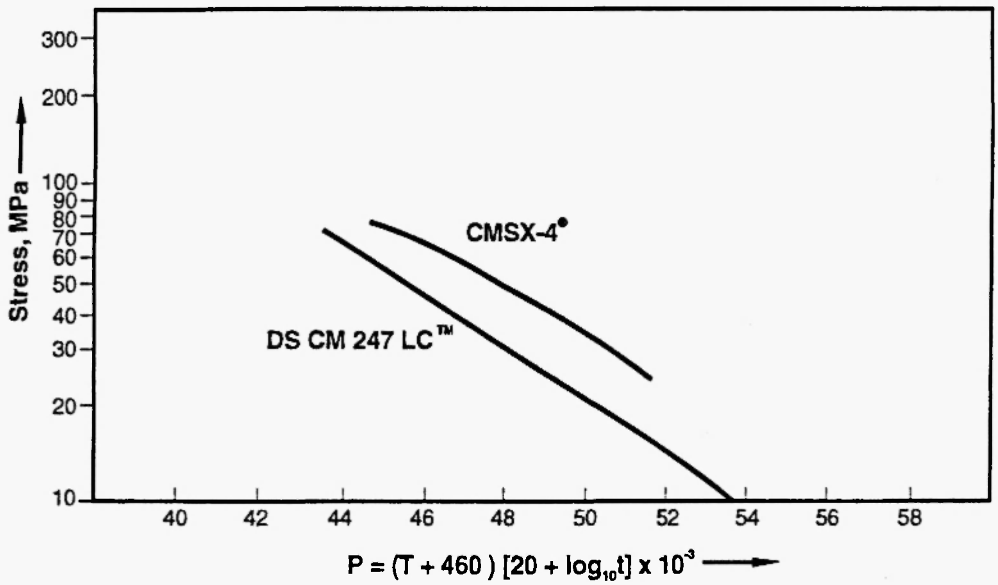

Fig. 3: Stress rupture properties of CMSX-4.

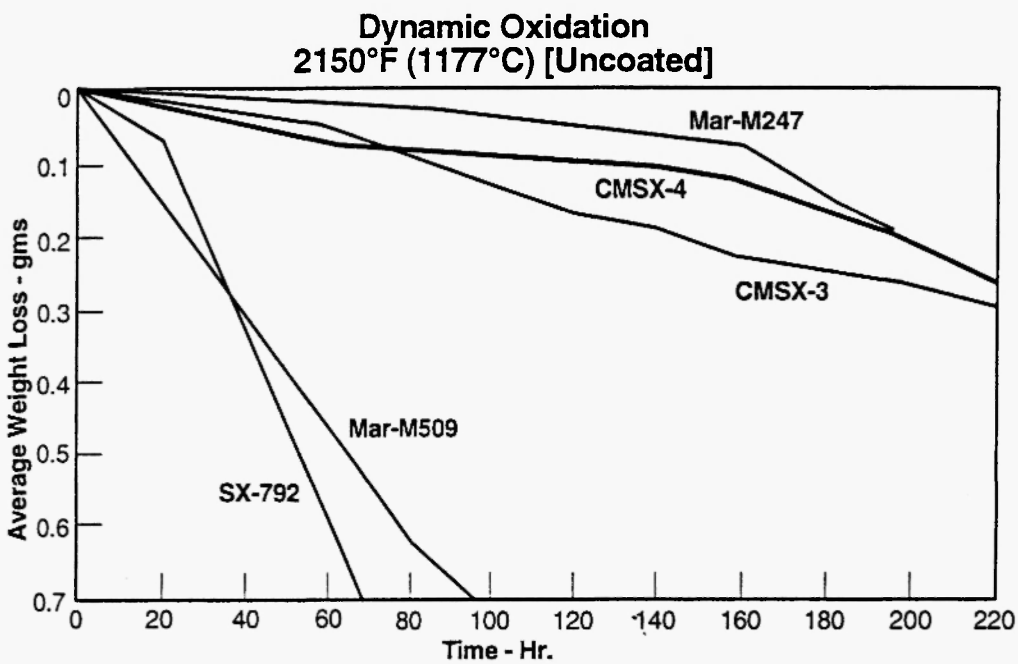

Fig. 4: Oxidation resistance of CMSX-4 compared to other alloys.

Table 4

Major Element Composition of DS Alloys
CM 247 LC® and CM 186 LC™

	Ni	Cr	Co	Ta	W	Mo	Al	Ti	Re	C	Zr	Hf
CM 247 LC	Bal	8.1	9.2	3.2	9.5	0.5	5.6	0.7	-	.07	.01	1.4
CM 186 LC	BA1	6.0	9.2	3.5	8.5	0.5	5.7	0.7	3.0	.07	.005	1.4

Since rhenium had shown great advantages in single crystal alloys, Harris and co-workers investigated its potential benefits in DS alloys. Resulting from this investigation was the CM 186 LC alloy, a DS alloy with 3% rhenium. The composition of CM 186 LC is shown in Table 4.

CM 186 LC exhibits in the DS form creep strength properties close to first generation single crystal alloy. These properties are shown in Fig. 6. This alloy is finding turbine engine applications as complex vane segment and long tip shrouded LP blades, which can be quite difficult to cast as single crystals.

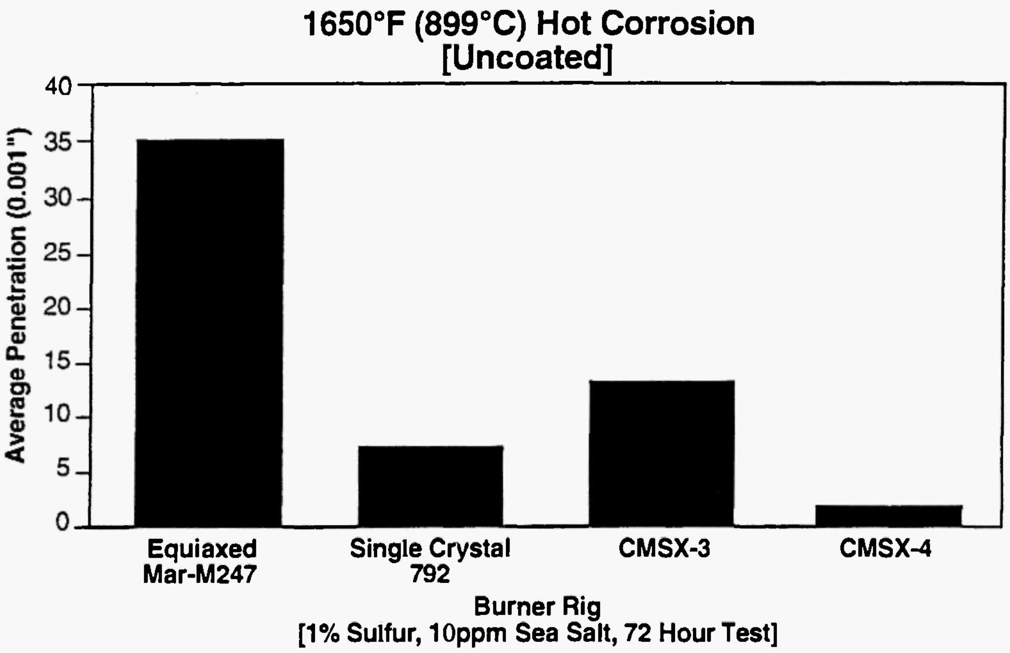

Fig. 5: Hot corrosion resistance of CMSX-4 compared to other alloys.

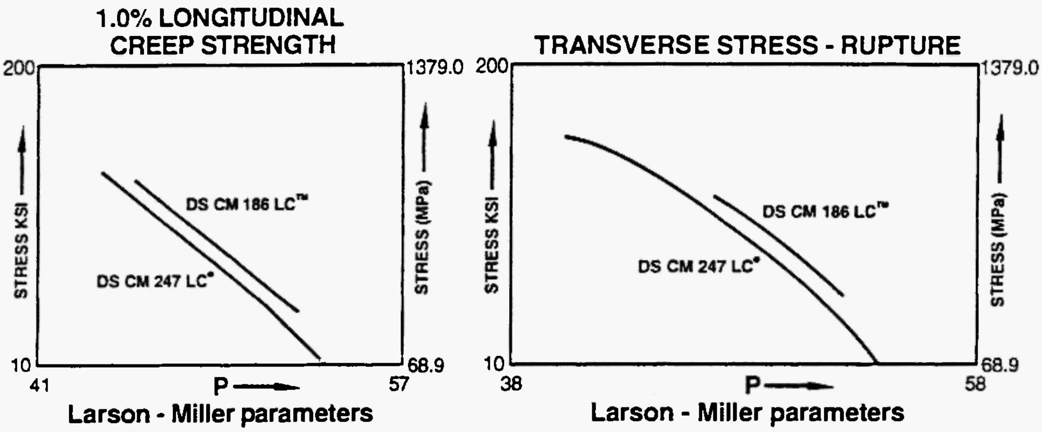

Fig. 6: Stress rupture properties of DS CM 186 LC compared to DS CM 247 LC.

3. SUMMARY AND CONCLUSIONS

Cannon-Muskegon has developed a series of single crystal and DS alloys including the following:

1. CMSX-2®, a first generation single crystal alloy with a wide heat treatment window.

2. CMSX-3®, which is CMSX-2® plus 0.1% hafnium added for aluminide coatability.

3. CMSX-6®, a low density single crystal alloy, unique in application where low density is paramount.

4. CMSX-4®, a rhenium containing single crystal alloy with strength properties 35 °C better than first generation alloys.

5. CM 247 LC®, a DS alloy which minimizes cracking on casting and which is able to be solutioned without incipient melting.

6. CM 186 LC™, a rhenium containing DS alloy which exhibits strength properties close to first generation single crystal alloys.

REFERENCES

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2. K. Harris, G.L. Erickson and R.E. Schwer, "Directionally Solidified and Single Crystal Superalloys", *ASM Metals Handbook* Vol. 1, 10th Edition (1989), p. 995-1006.