

Advancements in Turbine Blading Materials for IGT Applications

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ABSTRACT

In an effort toward achieving global competitiveness, most producers of advanced gas turbine power generating machines have begun to employ higher technology materials in critical engine components, thereby allowing increased turbine operating temperatures and pressures, which, in turn, lead to increased turbine efficiency. Additionally, the introduction of the emerging materials also results in an increased level of machine reliability. In the case of turbine blades and vanes, most producers are developing experience with Ni-based directionally solidified columnar grained (DS) and/or single crystal (SX) superalloys, since they are able to provide as much as 150° C increased temperature capability in relation to their polycrystalline counterparts. Of those materials which are considered, this narrative discusses the industries' developing experience with the CM 247 LC®, CM 186 LC®, CMSX-4®, CMSX®-10, CMSX®-11B and CMSX®-11C alloy systems. Specific component experiences are described through discussion of respective castability, heat treatment, mechanical properties, environmental properties and material issues.

NOMENCLATURE

AC	Air cool
ATS	Advanced Turbine Systems
CMSX®	Cannon-Muskegon Single Crystal
° C	Degrees Centigrade
DOE	Department of Energy
DS	Directionally solidified, columnar grain
° F	Degrees Fahrenheit
gm/cm ³	Grams per cubic centimeter - density
h	Hour

hrs	Hours
IGT	Industrial Gas Turbines
ksi	Thousands pounds per square inch
mm	Millimeter
MPa	Mega-pascals
MW	Mega-watts
nm	Nanometers
%	Percent
P	Larson Miller parameter
ppm	Parts per million
Re	Rhenium
SX	Single crystal
TCP	Topologically close-packed phase
TMF	Thermo-mechanical fatigue
γ	Gamma phase
γ'	Gamma prime phase
wt.%	Weight percent
C	Carbon
B	Boron
Zr	Zirconium
Hf	Hafnium
W	Tungsten
Mo	Molybdenum
Ta	Tantalum

INTRODUCTION

The equipment currently provided to the Industrial Gas Turbine (IGT) industry is expected to provide increased efficiency, reduced emissions, decreased life cycle costs and a high level of reliability. To meet the market's demand, the producers of gas turbine

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machines must employ advanced materials, in tandem with increasingly sophisticated turbine hot section designs.

While there are many aspects to turbine hot section design, this narrative is focused on the industry activity involving the advanced materials utilized in turbine blade and vane castings.

These materials are currently investment cast within withdrawal casting processes (Figure 1) which effect a nearly planar solidification front, eventually resulting in nicely aligned columnar grains or single crystals, as depicted in Figure 2. The grain-manipulated structures effect tremendous relative gain to creep-rupture, thermal fatigue and hot corrosion resistance (Figure 3), thereby translating into increased temperature capability and enhanced durability, eventually leading to more attractive life-cycle costs.

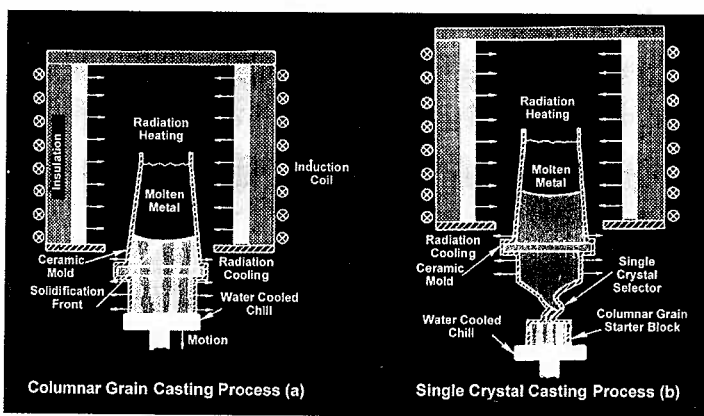


Figure 1 - DS Columnar Grain and Single Crystal withdrawal-method casting processes.

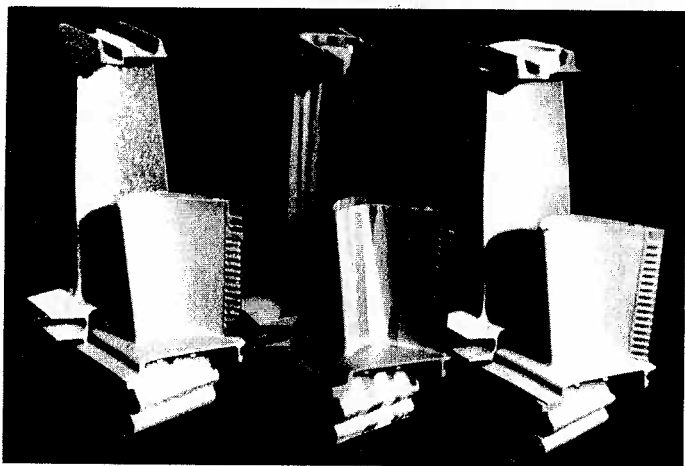


Figure 2 - The evolution of the processing of nickel-base superalloy turbine blades. From the left, equiaxed, directionally solidified columnar grain and single-crystal blades.

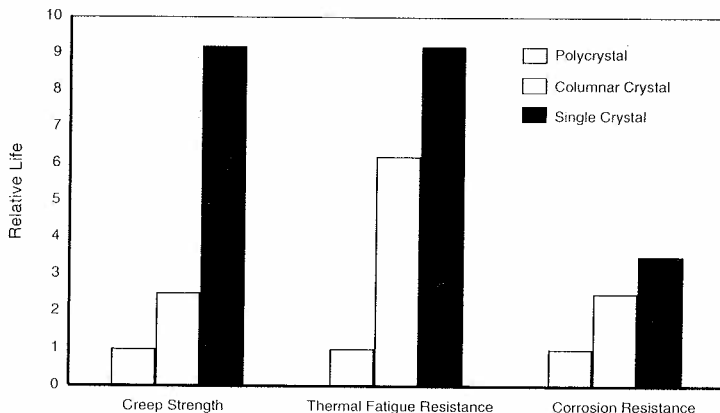


Figure 3 - Comparative properties of polycrystalline, DS columnar grain and single crystal superalloys (Gell et. al, 1987).

In recent years, Cannon-Muskegon Corporation has developed several superalloys which are specifically designed for directionally solidified, high temperature turbine components. While these materials are currently utilized in a wide array of both aero-turbine and land-based turbine applications, this narrative provides a brief review of the developing experience within the land-based, power generation community.

MATERIAL IDENTIFICATION

Most power generation machine producers have begun to employ directionally solidified products within their turbines. The grain-aligned materials replace previously utilized polycrystalline cast products produced with alloys, such as IN 738 C/LC, IN 792 and others which are provided in Table I.

The materials, which are available to the industry, were developed with varied design approaches, ultimately meaning that they each offer different blends of strength, hot corrosion and oxidation resistance. Furthermore, industry experience has demonstrated varied component castability, heat treatability and protective coatings performance, amongst the available alloys.

The alloys which are commercially utilized in industrial turbines are presented in Tables II and III. Those listed in Table II represent first and second generation DS columnar grain casting alloys (1st Generation -- no rhenium alloying, 2nd Generation -- 3.0 wt. % rhenium alloying) while Table III presents the commercially used and/or evaluated first, second and third generation single crystal casting materials.

	C	Cr	Co	Mo	W	Re	Ta	Cb	Al	Ti	B	Zr	Hf	Ni	Si	Mn	Fe	Y ₂ O ₃
IN 738 LC	.010	16.0	8.4	1.7	2.5	-	1.7	0.7	3.6	3.4	.010	.05	-	BASE	-	-	-	-
IN 939	.15	22.5	19.0	-	2.0	-	1.4	1.0	1.9	3.7	.010	.10	-	BASE	-	-	-	-
IN 792	.14	12.7	9.0	2.0	4.2	-	4.2	-	3.4	4.1	.015	.05	1.0	BASE	-	-	-	-
René 80	.17	14.0	9.5	4.0	4.0	-	-	-	3.0	5.0	.015	.03	-	BASE	-	-	-	-
MM 002	.15	9.0	10.0	-	10.0	-	2.5	-	5.5	1.5	.015	.05	1.5	BASE	-	-	-	-
MAR M 247	.15	8.0	10.0	.6	10.0	-	3.0	-	5.5	1.0	.015	.03	1.5	BASE	-	-	-	-
GTD 111	.10	14.0	9.4	1.5	3.7	-	3.0	-	3.0	5.0	.010	.01	.15	BASE	-	-	-	-
FSX 414	.25	29	BAL	-	7.5	-	-	-	-	-	.005	-	-	11	.9	.4	.9	-
MA 6000	.05	15	-	2.0	4.0	-	2.0	-	4.5	2.5	.01	.15	-	BASE	-	-	-	1.1
IN 713 C	.10	13.5	-	4.2	-	-	-	2.2	6.1	0.8	.010	.06	-	BASE	-	-	-	-

Table I. - Nominal compositions of selected polycrystalline casting alloys.

	C	Cr	Co	Mo	W	Re	Ta	Cb	Al	Ti	B	Zr	Hf	Ni	Reference
IN 792	.14	12.7	9.0	2.0	4.2	-	4.2	-	3.4	4.1	.015	.05	1.0	BASE	
René 80 H	.07	12.9	9.6	4.0	4.9	-	-	-	3.0	4.5	.015	.01	.75	BASE	
MAR M 247	.15	8.0	10.0	.6	10.0	-	3.0	-	5.5	1.0	.015	.03	.15	BASE	
CM 247 LC®	.07	8.1	9.2	.5	9.5	-	3.2	-	5.6	0.7	.015	.015	1.4	BASE	Harris, K.
CM 186 LC®	.07	6.0	9.0	.5	8.0	3.0	3.0	-	5.7	0.7	.015	.005	1.4	BASE	Harris, K. & Erickson, G.L.
René 142	.12	6.8	12	1.5	4.9	2.8	6.35	-	6.15	-	.015	.02	1.5	BASE	Ross, E.W. & O'Hara, K.S.
MAR M 200Hf	.13	8.3	9.3	-	11.7	-	-	0.9	5.0	1.9	.015	.01	1.8	BASE	
PWA 1426	.1	6.5	12.5	1.7	6.5	3	4	-	6	-	.015	.1	1.5	BASE	Cetel, A.D. and Duhi, D.N.
GTD 111	.10	4.0	9.4	1.5	3.7	-	3.0	-	3.0	5.0	.010	.01	.15	BASE	

Table II. - Nominal compositions of selected first and second generation DS alloys.

Alloy	Cr	Co	Mo	W	Ta	Re	V	Nb	Al	Ti	Hf	Ni	Density (kg/dm ³)	Reference
First Generation														
PWA 1483	12.8	9	1.9	3.8	4	-	-	-	3.6	4.0	-	Bal.	-	Duhl, D.N. and Gell, M.L.
CMSX-2 [®]	8	5	0.6	8	6	-	-	-	5.6	1.0	-	Bal.	8.56	Harris, K. and Erickson, G.L.
CMSX-3 [®]	8	5	0.6	8	6	-	-	-	5.6	1.0	0.1	Bal.	8.56	Harris, K. and Erickson, G.L.
CMSX [®] -11B	12.5	7	0.5	5	5	-	-	0.1	3.6	4.2	0.04	Bal.	8.44	Erickson, G.L.
CMSX [®] -11C	14.9	3	0.4	4.5	5	-	-	0.1	3.4	4.2	0.04	Bal.	8.36	Erickson, G.L.
Second Generation														
CMSX-4 [®]	6.5	9	0.6	6	6.5	3	-	-	5.6	1.0	0.1	Bal.	8.70	Harris, K. and Erickson, G.L.
PWA 1484	5	10	2	6	9	3	-	-	5.6	-	0.1	Bal.	8.95	Cetel, A.D. and Duhl, D.N.
MC2	8	5	2	8	6	-	-	-	5.0	1.5	-	Bal.	8.63	Caron, P. and Khan, T.
René N5	7	8	2	5	7	3	-	-	6.2	-	0.2	Bal.	NA	Wukusick, C.S. and Buchakjian, Jr., L.
Third Generation														
CMSX [®] -10	2	3	.4	5	8	6	-	.1	5.7	.2	.03	Bal.	9.05	Erickson, G.L.

Table III. - Nominal compositions of three generations of single crystal superalloys which are used and/or considered for industrial gas turbines.

MATERIAL CHARACTERIZATION

Directionally Solidified, Columnar Grain Casting Alloys

Most of the alloys previously used in the hot section blade and vane components for industrial turbines have contained relatively high levels of chromium, since Type II hot corrosion concerns predominated with the temperature/pressure operating conditions which prevailed. With the current design trend being toward increased turbine temperature/pressure designs, it appears that Type I hot corrosion commands greater concern, thereby allowing the usage of lower chromium-containing materials. Moreover, further accommodation for lower Cr-containing materials results from the widespread utilization of cleaner fuels, such as natural gas, and the significant advances realized in protective coatings technology.

This consequence is fortuitous, since early attempts to produce DS components with the high Cr alloys, such as IN 738 LC and IN 939, were not successful. Furthermore, it does not appear that the moderately alloyed IN 792 Hf and René 80H alloys have been universally successful; particularly not in large components where DS castability is of paramount importance.

This has left only a few DS materials available to the current-day industrial turbine designer; those remaining in Table II, such as CM 247 LC, MAR M 200 Hf, GTD 111, CM 186 LC, René 142 and PWA 1426. Of these, the only independently available materials are CM 247 LC, CM 186 LC, MAR M 247 and MAR M 200 Hf; the other compositions being owned by either United Technologies or General Electric.

For the four aforementioned independent materials, the CM 247 LC and CM 186 LC alloys provide improved characteristics relative to MAR M 247 and MAR M 200 Hf, such as better DS castability, heat treatability and strength.

CM 247 LC Alloy. Some industrial turbine producers utilize turbine blades and vanes produced with the CM 247 LC alloy in newly designed and updated turbines. When cast into large DS components [(approximately 30-51 cm (12-20" long)], the alloy exhibits superior castability, solution characteristics and strength attainment. With a relatively ductile, high chromium-containing coating applied, components have exhibited extremely good resistance to hot corrosion attack. Furthermore, where natural gas is the predominant fuel, the material hot corrosion requirements are significantly less than those cases where low grade fuels containing corrosion accelerators such as vanadium, sulfur and sodium predominate, so that high temperature oxidation becomes the increasingly important environmental concern.

The CM 247 LC composition is derived from the base MAR M 247 composition. The primary CM 247 LC alloy design modifications are the reduction of carbon by approximately one-half to improve carbide microstructure, stability, and alloy ductility, plus the reduction of the Zr and Ti contents to improve DS grain boundary cracking resistance without sacrificing strength. Additionally, the alloy's W and Mo levels are reduced accordingly to minimize the formation of undesirable secondary M₆C platelets,

Alloy	Cr	Co	Mo	W	Ta	Re	V	Nb	Al	Ti	Hf	Ni	Density (kg/dm ³)	Reference
First Generation														
PWA 1483	12.8	9	1.9	3.8	4	-	-	-	3.6	4.0	-	Bal.	-	Duhl, D.N. and Gell, M.L.
CMSX-2 [®]	8	5	0.6	8	6	-	-	-	5.6	1.0	-	Bal.	8.56	Harris, K. and Erickson, G.L.
CMSX-3 [®]	8	5	0.6	8	6	-	-	-	5.6	1.0	0.1	Bal.	8.56	Harris, K. and Erickson, G.L.
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μ phase and/or alpha W platelets or needles, resulting from the thermally induced degeneration of primary carbides. This degeneration of low parameter MC-1 (Ti-rich) and MC-2 (Ta-rich) carbides results in the formation of MC-3's (Hf-rich) with an associated release of Ta and Ti to the solid solution, thereby affecting the solubility of the W and Mo within the basic gamma solid solution, the result of which is the possible formation of thermally induced μ phase, alpha W and/or M_6C .

The alloy design results in extremely good DS castability; this being accomplished with the relatively low Hf ingot content of 1.4 wt. %. Furthermore, the alloy is capable of exhibiting similar functionality with a 1.0% Hf level in the DS castings (Erickson, 1984), the significance of which is that alloys with higher levels of Hf (> 1.5%) tend to be much more reactive with casting process-related shell and core ceramics, thereby resulting in component-contained Hf-oxide/Hf silicate inclusions which deleteriously affect component fatigue strength and casting yield. Moreover, alloy tolerance to varied Hf content is important since it generally varies significantly from blade/vane top to bottom sections.

The CM 247 LC alloy can be fully γ' solutioned through multi-step treatment (Erickson et al., March 1985). The full solutioning provides an increased volume fraction of fine γ' particles, which positively influence the alloy's creep-rupture response. An example of the alloy's 982° C stress-rupture capability is provided in Figure 4 with comparisons to IN 738 LC and CMSX-4, respectively. Additionally, the CM 247 LC Mach 1.0 cyclic oxidation characteristic is shown in Figure 5 for tests performed to about 300 hours at 1135° C.

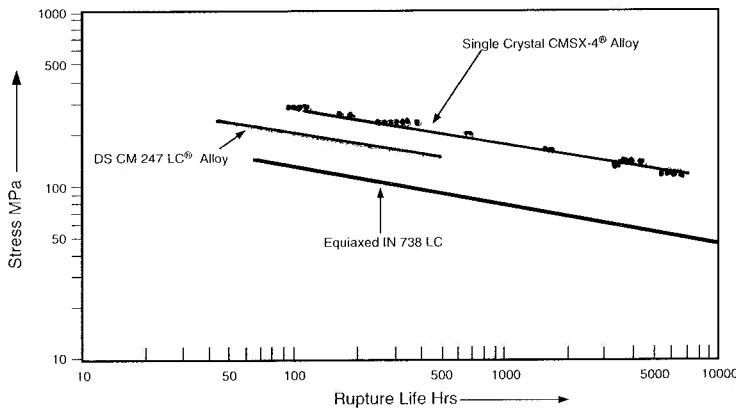


Figure 4 - 982° C stress-rupture for CMSX-4 vs. DS CM 247 LC vs. equiaxed IN 738 LC.

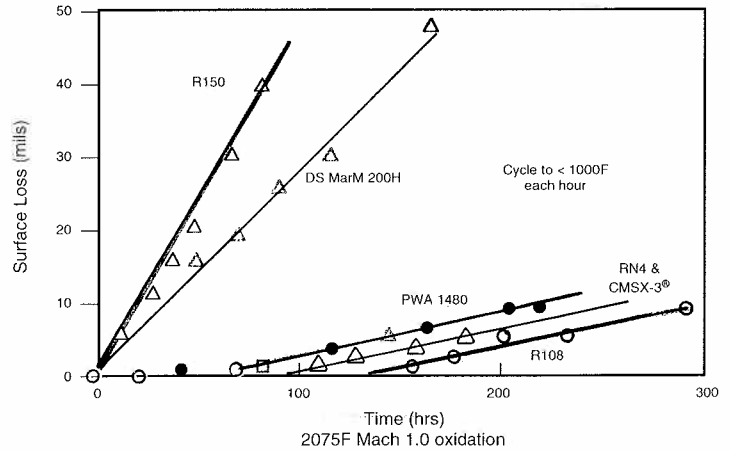


Figure 5 - DS CM 247 LC (R 108) Mach 1.0 oxidation (Ross, E.W., and O'Hara, K.S., 1992).

CM 186 LC Alloy. The CM 186 LC alloy is a Re-containing derivative of the CM 247 LC alloy. It is primarily intended for DS columnar, complex-cooled vane segments and relatively large LP turbine blade components. Additionally, it is particularly attractive for use in components which are prone to recrystallization during solution heat treatment (resulting from residual casting stresses), since the alloy is used in the as-cast plus double aged condition.

The alloy exhibits excellent resistance to grain boundary cracking in casting complex-cored, thin wall turbine airfoils. It is fully solution heat treat capable, however, at the expense of transverse ductility. Hence, the specified use in an as-cast plus double aged condition.

In this condition, CM 186 LC exhibits a 18° C metal temperature advantage relative to fully solutioned DS CM 247 LC at the 982° C/248 MPa test condition, and 24° C greater capability based on time to 1.0% plastic strain. This strength level mirrors that typically exhibited by first generation single crystal alloys, such as CMSX-2®, CMSX-3®, PWA 1480, René N4, SRR99, AM1 and others. For higher temperatures, its typical strength is about midway between the DS CM 247 LC and CMSX-2/3 respective capabilities (Fig.6).

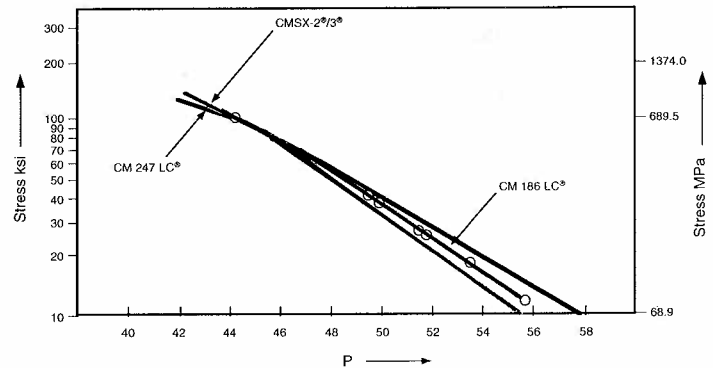


Figure 6 - CM 186 LC vs. CM 247 LC vs. CMSX-2/3 (001) DS longitudinal Larson-Miller stress-rupture.

The Directionally Solidified CM 186 LC alloy typically exhibits 7-14% elongation in DS transverse stress-rupture tests performed between 871° C-1038° C. The alloy's transverse strength is approximately 19° C better than the DS CM 247 LC transverse rupture capability.

The most significant feature of the CM 186 LC alloy is its 3.0% Re content. Rhenium addition to Ni-based alloys (3 wt. % level) dramatically increases alloy creep strength due to its effect of reducing γ' particle coarsening rate (Erickson et al., February 1985) and the clustering of Re atoms which develop, thereby impeding dislocation movement (Blavette et al., 1988). Beyond this, the CM 186 LC alloy design is similar to the respective features previously detailed for the CM 247 LC alloy. The alloy's oxidation resistance is superior to MM 002, while hot corrosion properties are similar to MAR M 247, CM 247 LC and MM 002. Furthermore, 10,000 hour duration creep-rupture tests reveal acceptable microstructural phasial stability prevails for the turbine operating conditions envisioned.

Single Crystal Casting Alloys

Additional combustion process efficiency benefits can be derived by employing single crystal blade and vane components in gas turbines. The benefits realized through the increasingly aggressive turbine operating temperature/pressures and design flexibility allowed through the use of single crystal components are the result of the increased creep strength, mechanical/thermal fatigue resistance, temperature capability and resistance to environmental degradation that such components can provide.

Typically, the alloy design concepts applied in single crystal alloy development are similar to those applied for DS casting materials. The exception, though, is that most single crystal alloys are designed with the elimination of elements, for which addition are intended primarily for grain boundary control. Therefore, the elements, C, B, Zr and Hf, are normally not included, although exceptions prevail due to efforts targeted toward improving casting yields through the allowability of greater off-orientation low angle boundaries with the re-introduction of some of these elements. Furthermore, since small additions of carbon are also beneficial toward the control of recrystallized grain growth in single crystal components, a myriad of slight modifications to the commercially utilized alloys has ensued.

In any case, the reduction of the aforementioned grain boundary strengthening elements to the "parts per million" (ppm) level is still desirable since they are melting point depressants. Their removal allows higher temperature solution cycles, which result in an increased level of γ' and eutectic γ/γ' solutioning, plus greater alloy microstructural homogeneity; both of which improve alloy creep strength. Such features should also provide further strength enhancing control of the γ' particle size, shape and distribution, similarly important toward high strength attainment.

The respective chemistries of the single crystal alloys, which are of general interest to the industrial turbine community, were presented in Table III. Similar to the situation which prevails for

the DS alloys, the only independent single crystal casting alloys which are commercially considered are those developed by Cannon-Muskegon Corporation, except for MC2, an alloy developed by ONERA in France. But currently, it does not appear that the MC2 alloy will achieve any commercial, power turbine applications. The discussion of single crystal alloys is, therefore, limited to the CMSX series of alloys.

While there are a couple of power generation applications for the CMSX-2 and CMSX-3 alloys, most industry interest is targeted toward the CMSX-4 alloy, followed by CMSX-10, CMSX-11C and CMSX-11B, respectively. CMSX-4 is widely used, but the alloy's largest volume industrial turbine utilizer is ABB in their GT-24 and GT-26 engines. Solar Turbines Inc. has applied the alloy in its turbines since 1990, with some CMSX-4 containing engines having accumulated more than 30,000 successful hours of operation. Many other major power generation machine producers are close to introducing the alloy into their commercial engines.

The application of the CMSX-10 alloy within industrial turbines is progressing. Rolls-Royce uses the alloy in their Industrial Trent, while Solar intends to utilize the alloy in their Mercury 50 engine (Fitzpatrick et al., 1997).

Industrial turbine application of the CMSX-11C alloy is expected within the next 1-2 years. Similarly, it currently appears that the CMSX-11B alloy may realize its first engine usage within the next 2-3 years.

Descriptives for each of these materials are provided.

CMSX-4 Alloy. The CMSX-4 alloy is a Re-containing modification of the CMSX-2 alloy. It exhibits a balanced blend of characteristics desired for successful usage in the investment casting foundry, and ultimate properties attainment desired for advanced turbine blade and vane components.

Relative to CMSX-2, the material is necessarily designed with moderately lower Cr content to reduce the likelihood of alloy phasial instability, i.e., the thermally induced precipitation of undesirable Cr, W, Re-rich TCP phases. Similarly, W content is reduced, but the overall refractory element (W+Re+Mo+Ta) content is significantly increased. Cobalt content is increased to 9 wt. % to assist with alloy solid solubility, while the remainder of the elements essentially remain the same.

The resulting alloy is capable of full γ' solutioning and exhibits a 35° C stress-rupture strength advantage in comparison to CMSX-2/3 at 982° C/248 MPa condition. The alumina scale forming alloy exhibits excellent high temperature oxidation resistance, while hot corrosion resistance is as good or better than IN 792, depending on test condition. Review of 30,000 hour run turbine blades confirm good coatability and base alloy phasial stability.

CMSX-4 components exhibit significantly better thermo-mechanical fatigue (TMF) properties relative to first-generation single crystal materials. Additionally, HIP treatment appears to improve TMF properties of the higher refractory element containing alloys, such as CMSX-4 and CMSX-10, by as much as 50%.

Besides the obvious benefit achieved with pore closure, a portion of this level improvement is due to the resultant increase to alloy homogeneity.

CMSX-10 Alloy. The CMSX-10 alloy is characterized by its relatively high refractory element content and more specifically, its 6 wt. % Re level. By virtue of its Re level, it is typically classified a third generation single crystal (SX) cast superalloy; second generation materials generally contain 3 wt. % Re, while first generation SX alloys contain none.

The composition of alloy CMSX-10 is compared to the nominal CMSX-4® composition in Table III. Notable differences between the second and third generation materials occur in their Cr, Co, Al + Ti and total refractory element levels. The primary compositional drivers giving rise to the alloy's enhanced creep strength are the material's 6% Re level in tandem with its elevated total refractory element content (W+Re+Mo+Ta) of about 20%.

Alloy CMSX-10 was designed to provide a satisfactory blending of the engineering characteristics necessary for successful turbine engine application. The alloy has proven to exhibit sufficient type I hot corrosion resistance and good oxidation resistance. Furthermore, it is very castable and also capable of full γ' and eutectic $\gamma - \gamma'$ solutioning without the occurrence of incipient melting. Moreover, these characteristics prevail while providing about 30° C improvement in creep and fatigue strengths relative second generation SX alloys such as CMSX-4.

The CMSX-10 alloy system is complex and the attainment of its optimized aim chemistry is crucial since the alloy's performance can be sensitive to minor chemistry fluctuations. The alloy's design encompasses an Al + Ti content of about 5.9%. The Ti alloy addition is necessarily low due to the elevated level of Ta desired in the alloy and the beneficial effect that low Ti provides toward solution heat treatment characteristics. Because CMSX-10 necessarily contains a high additive level of W+Re+Mo+Ta for strength attainment, its cobalt and chromium levels are designed consistent with the avoidance of excessive topologically-close-packed (TCP) needle phase formation. The resulting levels, about 2% Cr and 3% Co, are uniquely low and novel in comparison to other Re containing superalloys.

Typical creep strength benefits occurring with Re alloyed materials are illustrated in Figure 7, where the 982° C/248 MPa 1.0% creep strengths for various non-Re and Re-containing alloys are illustrated. For example, while 1.0% creep deformation occurs in about 28 hours in the non-Re containing CMSX-2 alloy, the same occurs in 130 hours in CMSX-4 (3% Re) and 600 hours in CMSX-10 (6% Re); improvements of 4.5 x and 20 x, respectively.

The long-term strength advantage of CMSX-10 over 2nd generation single crystal alloy CMSX-4 is maintained at temperatures below 982° C. Figure 8 is a comparative stress rupture plot which shows the substantial strength advantage of two rhenium containing single crystal alloys in relation to conventional polycrystalline and DS columnar grained alloys at 982° C. In longer-term tests at 982° C (or in tests conducted at higher

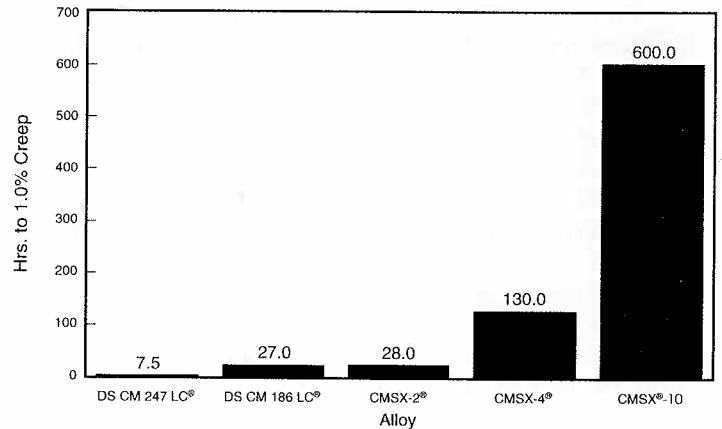


Figure 7 - Plot comparing 1% creep strength of Re and non-Re containing alloys (982° C/248 MPa)

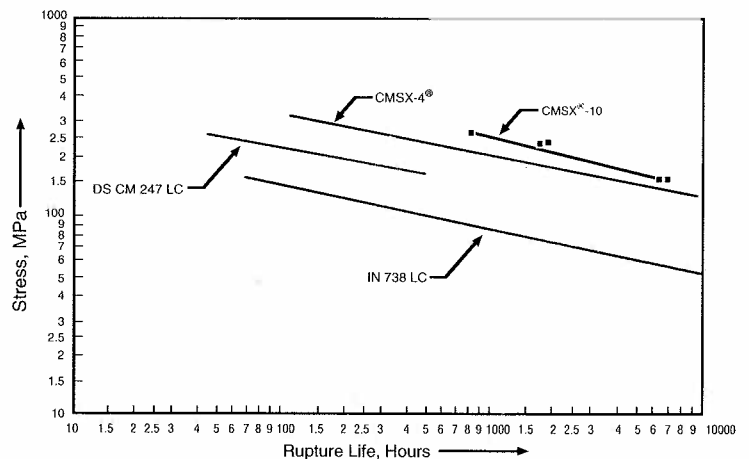


Figure 8 - Plot of time to rupture vs. applied stress at 982° C for several turbine blade alloys.

temperatures), it appears TCP phase formation begins to impact the strength of CMSX-10. For example, the data in Figure 8 shows that CMSX-10 has a 45 MPa strength advantage for failure in 800 hours, but the curves tend to converge with the stress vs. life curve for CMSX-4. However, at lower temperatures, which are more representative of IGT application, it is anticipated that alloy CMSX-10 will maintain a useful strength advantage relative to CMSX-4. As confirmation, several long-term rupture tests are underway at temperatures relevant to IGT blade design, with specimens currently running in excess of 20,000 hours.

CMSX-11B and CMSX-11C Alloys. While most of the single crystal alloys which were detailed in Table II were initially developed for aeroturbine application, the CMSX-11B and CMSX-11C alloys were developed specifically for usage in land based turbines. The alloys were designed to service the developing need for turbine vane and blade materials, which require a good blend of Type I hot corrosion and oxidation resistance, together with attractive long-term strength and low cost.

To this end, two non-Re containing single crystal alloys were developed. Both alloys contain a relatively high level of chromium, which assists toward achieving good environmental properties; plus, the designs include the selection of low molybdenum level, moderate tantalum and elevated Ti/Al ratio. Relatively high Al + Ti levels were employed, which in tandem with moderate alloy Ta level, helps provide the high strength achieved. Furthermore, the alloys' respective designs are thought to result in lower γ/γ' lattice misfit parameters than those typically prevailing with second generation SX materials, thereby affecting surprisingly good stress-rupture characteristics in at least the 980-1040° C test regime.

Similarly, the alloy systems employ moderate tungsten levels for solid solution strengthening, however, the alloys also engage Ta:W ratios greater than unity to assist with SX component castability. Partly necessitated by the relatively high chromium levels employed, and the desired levels of W + Ta content, alloy cobalt levels are set relatively low to ensure adequate microstructural stability.

The alloys do not rely on Re addition for strength attainment and may, therefore, exhibit longer lives and utility in certain components, due to their inherently lower tendency for phase instability in the temperature regime where Re-containing alloys tend to form Topologically-Close-Packed (TCP) phase. Figure 9 illustrates the specific or density corrected strengths of several commercial alloys in comparison to the CMSX-11 materials. Perhaps of most significance, the CMSX-11B alloy's strength is shown to equal or exceed that of CMSX-4, while the higher Cr containing CMSX-11C alloy appears superior to CMSX-4 only at higher temperatures, such as 982-1038° C.

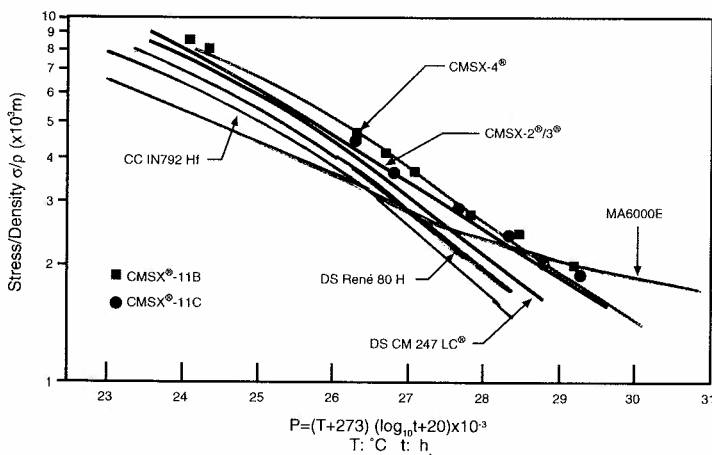


Figure 9 - Density corrected stress-rupture strength of several alloys.

Along this line, non-density-corrected log stress vs. log time rupture strength comparison of the IN 738 LC, DS CM 247 LC, CMSX-4 and CMSX-11B alloys at 982° C is shown in Fig. 10. Interestingly, the non-Re containing CMSX-11B alloy is shown to exceed the CMSX-4 alloy's rupture strength for tests run to between 1500-2000 hours life. Although not shown, the CMSX-11B alloy

1% average creep strengths demonstrated in these tests were not quite as good as the averaged CMSX-4 capability; however, two of the four test results did not lag significantly. Similarly, Fig. 11 compares the log stress vs. log rupture life of CMSX-4 and CMSX-11B for tests performed at 1038° C (also without density correction), and illustrates a significant advantage occurring with CMSX-11B for a test run to about 3000 hours. As comparative CMSX-4 alloy creep data is not available for the given test, future efforts will define the CMSX-4 alloy's creep-rupture characteristic, as well as expand the CMSX-11B data base in the 1038° C - 1100° C temperature regime.

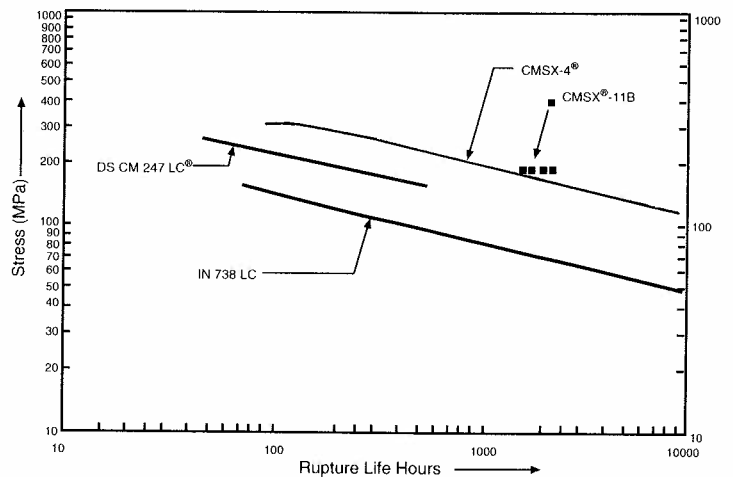


Figure 10 - 982° C stress rupture strength of several alloys.

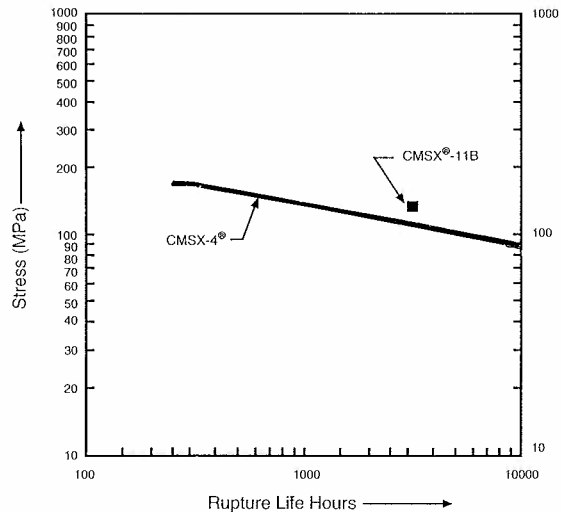


Figure 11 - 1038° C stress-rupture strength comparison of CMSX-11B and CMSX-4.

The results of extremely aggressive burner rig hot corrosion tests performed to 500 hour duration at 1050° C are shown in Fig. 12. Hot corrosion results are presented through comparison to other widely used gas turbine alloys, such as FSX-414, DS René 80 H,

DS IN 738 LC, DS IN 939 and DS CM 186 LC. The actual corrosion results are presented in terms of test specimen thickness loss, while the respective material's strength capabilities are expressed on the figure's y-axis as creep-rupture temperature capabilities for 1000 hour lives with a testing stress of 284.4 MPa. For this testing, the figure illustrates that the CMSX-11C alloy develops DS René 80 H type hot corrosion resistance with an attendant 25° C strength advantage. The CMSX-11B alloy does not provide quite as good hot corrosion capability in the test, but is significantly better than the DS CM 186 LC alloy, a material also considered for some industrial turbine applications.

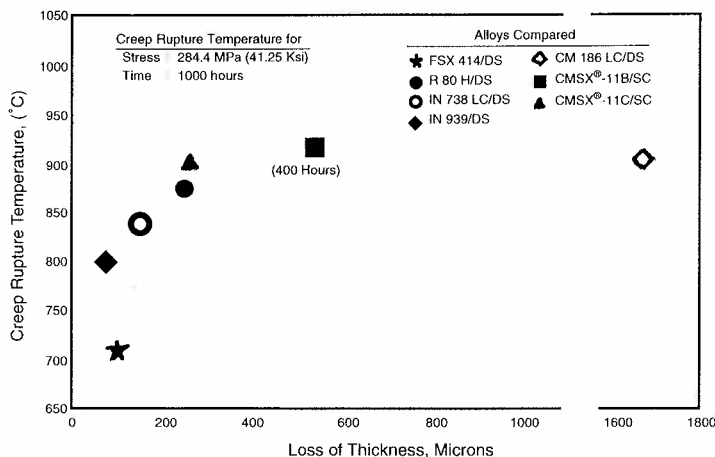


Figure 12 - Alloy strength and 1050° C/500 hour burner rig hot corrosion comparison of several alloys.

Burner rig oxidation test results are shown in Fig. 13. The alloys compared (along with the result presentation methods employed) are identical to those presented in Fig. 12. For this run at 1200° C and exposure of 500 hours, the CM 186 LC alloy is shown to exhibit the best alloy oxidation resistance, with the CMSX-11B and CMSX-11C materials behaving quite similarly; a unique capability for materials exhibiting IN 738/IN 792/René 80 type corrosion resistance. To that point, Fig. 13 also exhibits the reduced oxidation resistance of the René 80 and IN 738 LC alloys in comparison to CMSX-11.

Confirmation of the CMSX-11 oxidation characteristic is provided in Fig. 14, where the results of a cyclic crucible test performed at 1000° C on the CMSX-11B, CMSX-11C and IN 738 LC alloys are presented. While the IN 738 LC alloy oxidation resistance is low, the two CMSX-11 alloy derivatives exhibit relatively good oxidation characteristic for the duration of the test, i.e., 3000 hours. While not presented, the Fig. 14 test data source has developed unpublished data at identical conditions for the PWA 1483 alloy, which show its capability appearing between the IN 738 LC and CMSX-11C test results.

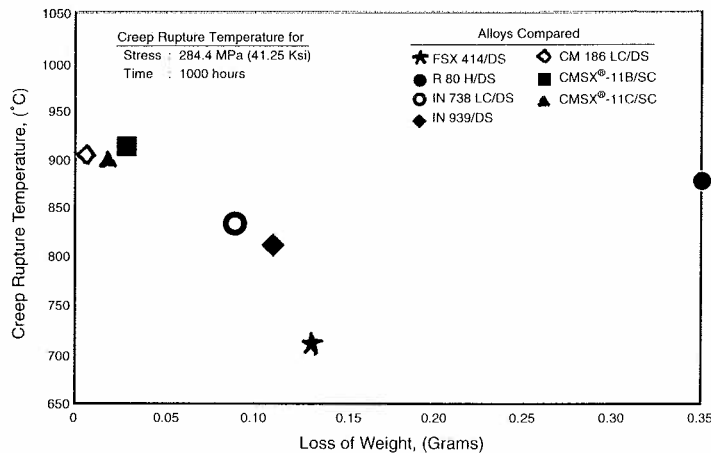


Figure 13 - Alloy strength and 1200° C/500 hour burner rig oxidation comparison of several alloys.

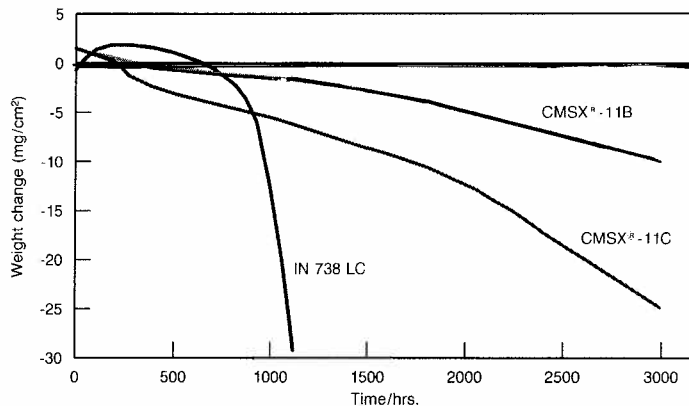


Figure 14 - 1000° C cyclic oxidation of three alloys.

The alloys, therefore, provide surprisingly good oxidation characteristics, as confirmed through both burner rig and crucible tests performed by multiple gas turbine engine manufacturers. At the same time, similar multiple source testing confirms both alloys exhibit very good hot corrosion capabilities (IN 738 LC/René 80/IN 792 level). The ability of the CMSX-11B and CMSX-11C alloys to provide good hot corrosion and oxidation characteristics, in tandem, is thought unique among available turbine materials.

FUTURE DIRECTION

Incremental improvements to the alloys currently available to the land based turbine industry will ensure their gainful application for a minimum of 15 years into the future. The improvements employed could consist of low level grain boundary strengthener additions to increase single crystal alloy component low angle boundary tolerance, low level rare earth element addition to improve alloy base oxidation resistance, minor chemistry modifications to enhance alloy substrate/coating compatibility and life, as well as the

usage of advanced overlay coatings to achieve longer component lives. Additionally, a better understanding and control of component manufacturing process technology will further benefit future turbine lives and overall component life-cycle costs.

SUMMARY

Several DS Columnar Grain and Single Crystal casting alloys are available for usage in new gas turbine designs and/or retrofits. All of the Cannon-Muskegon developed materials provide good component producibility and associated processing functionality. A wide array of property blends and cost levels are available for gas turbine designers to choose from.

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