THE DEVELOPMENT AND APPLICATION OF CMSX®-10

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Abstract

The CMSX®-10 alloy is a third generation single crystal (SX) casting material which is used in demanding turbine engine blading applications. The flight engine certified alloy is characterized by it's 6 wt. % rhenium content, high additive refractory element level, and relatively low chromium employment. Based on published data, the alloy is thought to exhibit the highest creep strength and resistance to fatigue of any production Ni-base, cast SX superalloy.

CMSX-10 alloy provides an approximate 30°C improved creep strength relative to second generation 3 wt. % containing SX alloys such as CMSX-4 and PWA 1484. Furthermore, it develops low cycle and high cycle fatigue (LCF and HCF) strengths as much as 2-3 times better than the best alternatives. Moreover, the alloy also develops an attractive blend of tensile and impact strengths, foundry performance, heat treatability and environmental properties characteristic. Most notably, the alloy provides surprisingly good hot corrosion resistance, despite its novel and relatively low chromium content (2-3 wt. %). Additionally, the alloy performs extremely well in both the aluminide and Pt - aluminide coated conditions.

Although the CMSX-10 alloy was developed to fulfill a perceived need in the aero-turbine industry, the alloy's long-term high strength, particularly at temperatures ranging from 850-950°C, has attracted significant industrial turbine interest. For this reason, longer term (currently to about 5000 hours) creep-rupture strength characterization is underway. Similarly, due to a continued need for materials with greater creep-strength, a higher strength CMSX-10 derivative, currently designated CMSX-10+, is under development.

This narrative characterizes the CMSX-10 alloy SX component castability, heat treatability, mechanical strength, environmental properties and coating characteristics. Active long-term creep-rupture programs are discussed, as well as preliminary results for a higher strength alloy, currently designated CMSX®-10+.

Introduction

The commercialization of the directional solidification casting process for turbine blade and vane manufacture resulted in the definition of many alloy designs seeking to maximize the benefit afforded with the directional structure. Foremost in this regard has been the definition of specific alloy formulations used in producing single crystal castings. Broadly, such materials began as simple modifications of polycrystalline and directionally solidified, columnar grained materials, with alloy complexity increasing with the ever-increasing results being sought.

The alloys initially defined were non-rhenium containing and generally afforded a 17-22 °C strength improvement relative to most directionally solidified, columnar grained materials. As the positive strengthening effects of Re alloying became more widely apparent, and the cost of Re metal became commercially viable, alloys containing about 3 wt. % Re ensued.

This category material containing 3 Wt. % Re (now referred to as second generation SX casting alloys), generally exhibited about 30-35°C improved strength in comparison to the so-called first generation SX alloys. These materials, such as CMSX-4, PWA 1484 and René N5, gained commercial significance in the latter part of the last decade, and continually realize new applications.

Although able to provide impressive strength, the second generation, 3 wt. % Re - containing superalloys were able to be improved upon through increased Re alloying. Partly stimulated by needs identified during new engine design for the recently introduced Boeing 777 wide body, twin engine aircraft, third generation SX alloys were defined.

Broadly, the new materials eventually found significance with Re level of about 6 wt. %. Successful alloys generally contain a high volume fraction of refractory elements while maintaining moderate Al + Ti content. Necessitated through concern for microstructural phasial stability, the alloys employ dramatically lower chromium content than second generation SX casting alloys.

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Superalloys 1996
Edited by R. D. Kissinger, D. J. Deye, D. L. Anton,
A. D. Cetel, M. V. Nathal, T. M. Pollock, and D. A. Woodford
The Minerals, Metals & Materials Society, 1996

The resulting third generation class of materials generally achieve an approximate 30°C strength improvement relative to their second generation alloy counterparts. Strength, stability and hot corrosion resistance varies for the materials identified, however, all appear to exhibit acceptable hot corrosion resistance, despite their uniquely low chromium contents.

The availability of these higher strength materials has allowed engine designers to replace cooled turbine blades with un-cooled designs, thereby increasing turbine efficiency due to the attendant reduction in the cooling-air requirement. Demonstration of this occurrence is provided by the Rolls-Royce use of the CMSX-10 alloy (RR 3000) in a hollow, uncooled IP blade component of the TRENT 800 series engine (1,2), where rather than utilizing a cooled CMSX-4 blade, RR determined that they could eliminate the blade cooling requirement by utilizing the higher strength CMSX-10 alloy.

As the industrial TRENT is designed utilizing the turbine core technology developed for the aero-turbine TRENT 800 (2), CMSX-10 industrial turbine application is thereby realized. Along this line, CMSX-10 alloy application in other industrial turbines (marine and or land-based) is also envisioned due to the significant long-term creep-strength advantage the alloy provides in the lower temperature regime normally predominating in industrial turbine high pressure turbine sections, as illustrated in Figure 1.

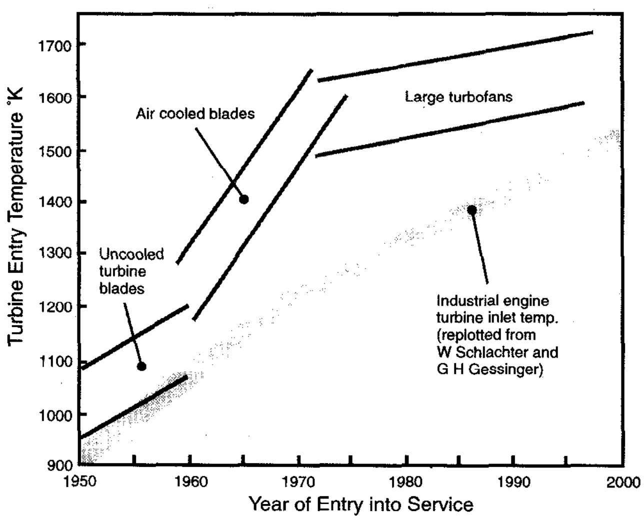


Figure 1: Comparison of civil aero engine take off temperatures and industrial engine turbine inlet temperatures (3).

ABB reports that relatively low turbine material temperatures (less than 900°C) prevail in their newly designed GT 24 and GT 26 engines (4). Similarly, other industrial turbine producing companies confirm typical hot section turbine operating temperatures ranging from 900 to 950°C (1652-1750°F), with relatively short-term exposure at higher temperatures (5).

As third generation alloys can exhibit phasial instability at elevated temperatures, the propensity for Topologically-Close-Packed (TCP) phase formation occurring during long-term industrial turbine operation has been an issue of concern. Most typically, third generation alloys tend to exhibit their greatest propensity for TCP phase formation with exposure at about 1090-1150°C (2000-2100°F). Moreover, as illustrated in Figure 2, TCP phase formation in the CMSX-10 alloy at 980°C and below is quite sluggish. Furthermore, microstructural review of specimens tested to about 5000 hours at 913°C shows a complete absence of TCP phase formation. Although longer-term test data continue to be developed, it appears at this point that third generation SX casting alloys such as CMSX-10 may, therefore, potentially offer great utility for usage in some industrial turbine designs.

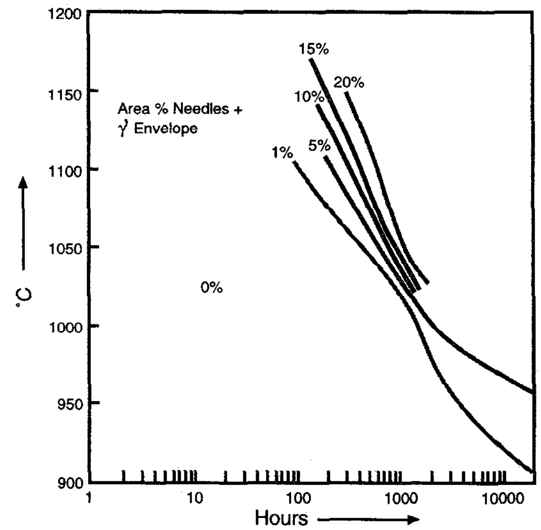


Figure 2: CMSX-10 alloy tendency for TCP phase formation.

To this end, the CMSX-10 alloy is under evaluation in the U.S. Department of Energy (DOE) funded Advanced Turbine Systems (ATS) Program. This effort is targeted toward developing and commercializing ultra-high efficiency, environmentally superior, cost-competitive gas turbine systems for base-load applications employing firing temperatures of 1427°C (2600°F) or greater. Moreover, the alloy system is also considered for evaluation by other individual industrial turbine engine producers throughout the world.

For aero-turbines (beyond the Rolls-Royce usage) the alloy is under consideration and evaluation by several turbine producers. As the strength requirements for the newest turbine designs continue to ascend, the need for a higher strength CMSX-10 alloy derivative has arisen, and is therefore under development. The higher strength alloy, currently designated CMSX-10+, provides an enhanced strength of about 8°C.

Alloy Design

Increasing alloy creep-strength beyond the levels exhibited by second generation SX casting superalloys requires an increase of Re alloying. Generally, it appears that moderate Re increases, ie., to levels of 4 or 5 wt. %, is ineffective toward promoting gains in creep capability sufficient to justify new alloy definition. Levels of 6 to 6.5 wt.. % appear the most feasible at this point, so the CMSX-10 alloy system is balanced around the inferred requirement. Along with the relatively high Re level employed, experience suggests that creep-strength optimization also requires increased levels of other refractory element hardeners such as W, Ta and Mo.

As W tends to be involved in TCP phase formation, its employment must be judiciously balanced with the predominating Re requirement. Moreover, since Cr also contributes to sigma phase formation, utilizing high Re + W content requires relatively low chromium alloying.

Since Cr is a significant contributor to alloy hot corrosion resistance, alloy Cr level selection must be carefully balanced to achieve the required alloy hot corrosion characteristic while being low enough to ensure adequate resistance to sigma phase formation.

Against these design constants, Mo and Ta alloying may be employed with increased latitude. However, as Mo is generally a negative factor for environmental properties, its employment is carefully scrutinized. Furthermore, since tantalum's atomic diameter is larger than Mo, it is a more efficient hardener. Significant Ta alloying is employed because of its beneficial effect in the SX casting process in reducing alloy freckle formation, plus it positively influences environmental property characteristics.

All told, the CMSX-10 alloy system employs the relatively high additive refractory element content of about 20.1 Wt.. %; this in comparison to CMSX-4 which is about 16.4% and CMSX-2 at 14.6%. Gamma prime formers such as Al and Ti are similar to second generation SX alloys and the CMSX-10 gamma prime chemistry is actually quite similar to that predominating for CMSX-4.

For this reason, creep-rupture properties of the CMSX-10 alloy at temperatures where gamma prime particle chemistry has a major influence to alloy creep resistance ie., relatively low temperatures (700-800°C), the alloy's properties are similar to CMSX-4. Additionally, the γ' particle chemistry characteristic implies that a significant level of Ta is distributed within the alloy matrix, thereby positively impacting solid solution strengthening.

This, in tandem with the high level of W + Re + Mo prevailing throughout the alloy matrix assists in the attainment of the extremely high creep-strength exhibited by the CMSX-10 alloy, particularly at elevated temperatures.

With TCP phase formation being a formidable issue in the design of third generation SX alloys, reduction in the tendency toward TCP phase formation is partially achieved through judicious selection of the cobalt aim composition. Prudent consideration of alloy Co + Cr content in a third generation alloy system can lead to attainment of acceptable alloy stability while maintaining high enough total refractory element content to achieve the desired alloy strength characteristics. Table I provides the CMSX-10 alloy chemistry in comparison to other first, second and third generation SX alloys.

Table I Nominal Compositions of Three Generations of Single-Crystal Superalloys (wt. %)

Alloy	Cr	Co	Mo	W	Ta	Re	V	Nb	Al	Ti	Hf	Ni	Density (kg/dm³)	Ref.
First Generation														
PWA 1480	10	5	–	4	12	–	–	–	5.0	1.5	–	Bal.	8.70	7
PWA 1483	12.8	9	1.9	3.8	4	–	–	–	3.6	4.0	–	Bal.	–	17
René N4	9	8	2	6	4	–	–	0.5	3.7	4.2	–	Bal.	8.56	8,9
SRR 99	8	5	–	10	3	–	–	–	5.5	2.2	–	Bal.	8.56	10,11
RR 2000	10	15	3	–	–	–	1	–	5.5	4.0	–	Bal.	7.87	10,11
AM1	8	6	2	6	9	–	–	–	5.2	1.2	–	Bal.	8.59	12
AM3	8	6	2	5	4	–	–	–	6.0	2.0	–	Bal.	8.25	13
CMSX-2®	8	5	0.6	8	6	–	–	–	5.6	1.0	–	Bal.	8.56	14
CMSX-3®	8	5	0.6	8	6	–	–	–	5.6	1.0	0.1	Bal.	8.56	14
CMSX-6®	10	5	3	–	2	–	–	–	4.8	4.7	0.1	Bal.	7.98	15
CMSX®-11B	12.5	7	0.5	5	5	–	–	0.1	3.6	4.2	0.04	Bal.	8.44	18
CMSX®-11C	14.9	3	0.4	4.5	5	–	–	0.1	3.4	4.2	0.04	Bal.	8.36	19
AF 56 (SX 792)	12	8	2	4	5	–	–	–	3.4	4.2	–	Bal.	8.25	16
SC 16	16	–	3	–	3.5	–	–	–	3.5	3.5	–	Bal.	8.21	20
Second Generation														
CMSX-4®	6.5	9	0.6	6	6.5	3	–	–	5.6	1.0	0.1	Bal.	8.70	21
PWA 1484	5	10	2	6	9	3	–	–	5.6	–	0.1	Bal.	8.95	22
SC 180	5	10	2	5	8.5	3	–	–	5.2	1.0	0.1	Bal.	8.84	23
MC2	8	5	2	8	6	–	–	–	5.0	1.5	–	Bal.	8.63	24
René N5	7	8	2	5	7	3	–	–	6.2	–	0.2	Bal.	NA	25
Third Generation														
CMSX®-10	2	3	.4	5	8	6	–	.1	5.7	.2	.03	Bal.	9.05	26
René N6	4.2	12.5	1.4	6	7.2	5.4	–	–	5.75	–	.15	Bal.	8.98	27

Alloy Manufacture

The CMSX-10 superalloy is manufactured in similar fashion to other single crystal casting alloys. The alloy's relatively high Re content does not present any new melting challenges other than raising the alloy liquidus temperature.

A standard CM VIM technique along the detail delineated in Ref 6 is utilized to produce the CMSX-10 superalloy. Greater than fifty (50) each 114-182 kg developmental VIM heats were produced and evaluated in the CMSX-10 alloy development program. The CMSX-10 alloy is a production status material with five production, 3.9 ton heats having been produced and sold (as of February 1996) as well as one 50% virgin/50% revert heat manufactured utilizing approximately 1800 kg of foundry process generated CMSX-10 alloy revert (runner systems and scrap blades).

As anticipated, the quality of the 50/50 product is nearly identical to that typical of 100% virgin. Table II offers a "window" toward defining alloy quality in that it presents the typical trace element levels achieved in the virgin and 50/50 production heat product. The only characteristics able to be differentiated among the alloy heats are in respective sulfur and heat oxygen contents. But of course, both levels are extremely good, and end-users realize significant alloy component cost improvements through the use of 50% virgin/50% revert alloy product.

Table II Typical Alloy Tramp Element Levels for 100% Virgin and 50/50 Revert Blends of CMSX-10 Alloy

Alloy	C	B	Zr	S	[N]	[O]
	←		wt. ppm			→
CMSX®-10* (100% V)	20	<20	<10	1	1	1
CMSX®-10+ (100% V)	20	<20	<10	1	1	1
CMSX®-10++ (50%/50% R)	22	<25	21	2	1	2

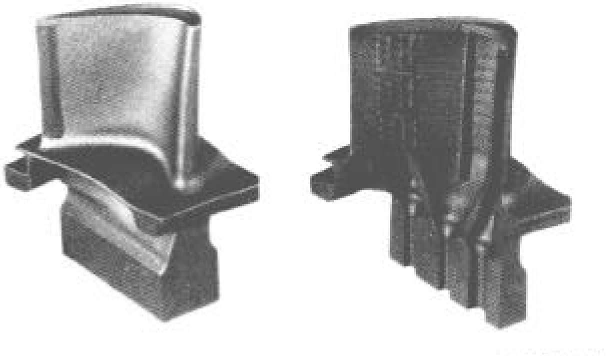
*Greater than 50 each developmental 114-182kg heats
+5 each 3.9 ton production heats
++1 each 3.9 ton production, 50% virgin/50% revert heat

Earlier 140 kg heat work seeking to determine the suitability of CMSX-10 alloy 50% virgin/50% revert alloy product usage illustrated that identical alloy mechanical properties are achieved with the 50/50 product vs. the 100% virgin counterpart. Confirmation of this is anticipated with the production process produced 50/50 product.

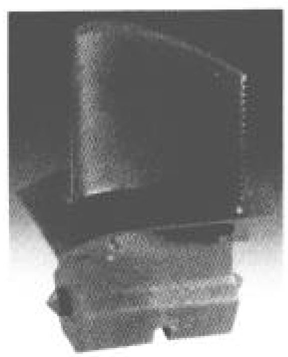
Casting Experience And Heat Treatment

With the CMSX-10 alloy being flight engine certified in the TRENT 890 engine, considerable production foundry experience with the alloy system prevails. While some platform low angle boundary defect difficulties were occasionally encountered when producing TRENT 890 engine IP blade components with the CMSX-10 alloy, relatively simple SX grain extenders resolved the problem which, incidentally, had also occurred with the CMSX-4 alloy. Manufacture of other turbine blading components at several investment casting foundries around the world demonstrates that the alloy's castability is similar to the second generation, CMSX-4 superalloy.

Further confirmation of the alloy's castability characteristics was achieved with development casting trials undertaken with Allison Engine Co. T56 engine first stage HPT cooled blades plus solid, second stage blade components as illustrated in Figure 3. Excellent experience with first stage Solar Turbines MARS engine blades (Fig. 3) cast at Howmet Corporation in Whitehall, MI has been obtained, while castability experience developed in Japan has been equally favorable. Successful castability experience with demonstrator engine blades has also been achieved, thereby further confirming favorable CMSX-10 foundry characteristics.



Allison AE 2100 1st stage HPT blade.



Allison AE 2100
2nd stage blade.

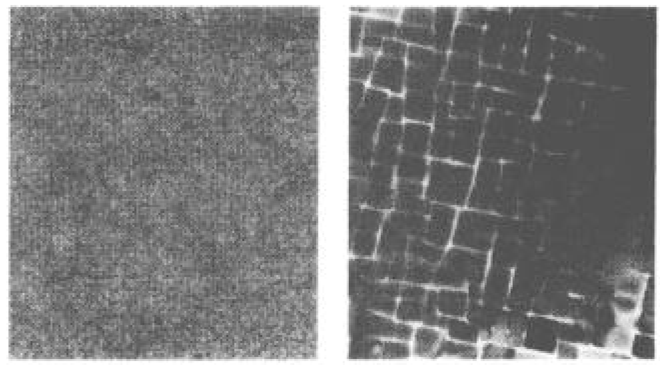
Solar® Mars 100 Engine
1st stage HPT blade.

Figure 3: Selected turbine blade configurations used to demonstrate the CMSX-10 alloy castability characteristic.

Besides possessing good SX castability characteristics, CMSX-10 alloy also provides attractive solution heat treatment capability. The alloy provides a 21 °C heat treatment window (numerical difference in °C between the alloys γ' solvus and incipient melting point) and is thereby able to be fully solutioned. Solution heat treatment, undertaken with a final soak temperature of 1366 °C, results in full coarse γ' solutioning plus complete eutectic γ-γ' dissolution. Re-precipitation of the dissolved γ' into a more useful fine γ' results, and primary aging of the fine γ' then occurs at 1152 °C.

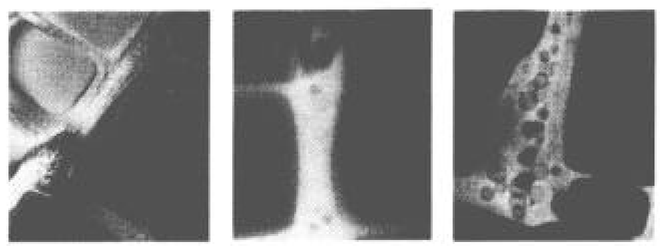
The CMSX-10 alloy primary γ' aging treatment helps develop an array of fine cubic γ' with relatively regular alignment, exhibiting average edge dimensions of about 0.5 μm. (Fig. 4). The primary aging treatment is followed by two secondary aging treatments which promote the formation of finer γ' within the alloy's matrix channels. These secondary aging treatments are preformed at 871 °C for 24 hours and at 760 °C for 30 hours.

The precipitates which develop through these aging conditions are relatively fine, and are likely dissolved within blade airfoil sections with normal service exposure at higher temperatures. However, as blade root sections do not normally experience exposures in the 760 to 870 °C regime, the γ' precipitates which are formed during the aforementioned aging processes prevail throughout turbine blade component life-cycles and are thought to contribute positively to component tensile and fatigue property characteristics. The small matrix channel precipitate occurring with the multiple step aging treatment is illustrated in Figure 5.



a 1μm b 500nm

Figure 4: Two views of fully heat-treated CMSX-10 alloy.



a 100nm b 50nm c 50nm

Figure 5: The CMSX-10 alloy aged at (a) 1,152 °C, (b) 1,152 °C + 871 °C and (c) 1,152 °C + 871 °C + 760 °C.

Further alloy developments seeking to identify a higher strength CMSX-10 alloy derivative led to the definition of the CMSX-10+ composition. Due to the design changes necessary to develop higher strength, the resulting alloy exhibits a narrower heat treatment window of approximately 8 °C. However, as the producers and users of high temperature solution heat treatment furnaces have improved new furnace designs, extremely good process temperature control (± 4 °C) within multiple layers or zones of vacuum heat treatment vessels are achieved. It thereby appears that, contrary to prior experience, alloys with relatively small heat treatment windows may be successfully heat treated on a production basis.

With successful solution heat treatment, relatively straight-forward aging cycles are applied to the newest, high-strength SX alloy system. Currently, the aging treatments applied to CMSX-10+ alloy articles are identical to those operative with CMSX-10, with nearly identical results.

Mechanical Properties

Increased superalloy Re alloying generally results in significant creep and fatigue strength improvements. However, as can be inferred from Figure 6, alloys with high solute element levels such as CMSX-10 do not necessarily exhibit improved alloy tensile properties. Similar to the CMSX-4 alloy, the CMSX-10 tensile strength peaks at about 760 °C while maintaining relatively good ductility throughout the tested regime.

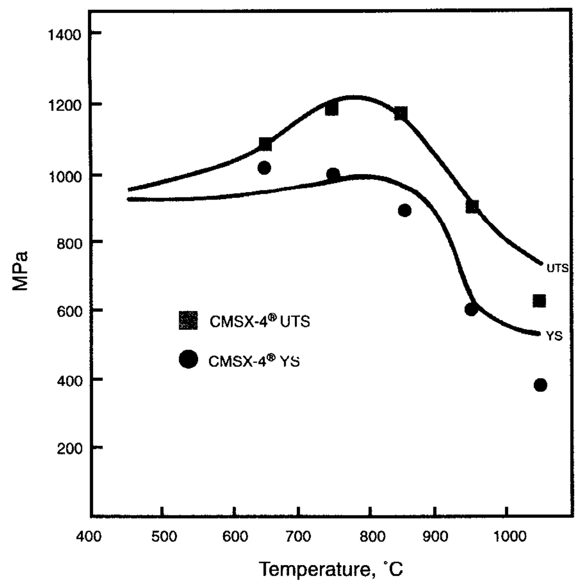


Figure 6: CMSX-10 tensile strength.

Similarly, superalloy impact properties do not appear to be dramatically influenced by increasing alloy Re content, as illustrated in Figure 7 with comparison of the CMSX-10 and CMSX-4 respective capabilities.

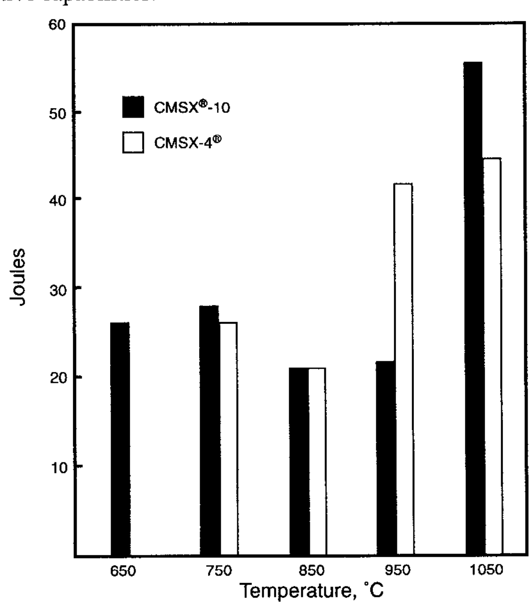


Figure 7: CMSX-10 impact strength. Cylindrical specimen, 7.2 mm diameter x 55 mm long.

Third generation SX casting alloys generally exhibit enhanced creep strength relative to their second generation predecessors. The relative improvement depends upon the alloy systems compared, but for CMSX-10, the advantage is about 30°C relative to CMSX-4. In terms of actual turbine engine operation, this advantage is shown quite dramatically through the difference in turbine blade growth occurring during an engine test for CMSX-10 vs CMSX-4 blades shown in Fig. 8.

In this particular test, identical CMSX-4 and CMSX-10 blades in a common blade ring were measured before and after the engine run. Analysis of the test data revealed average CMSX-4 blade growth

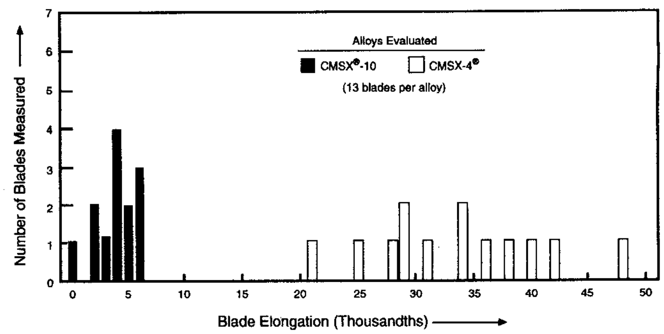


Figure 8: Post turbine engine test blade growth measurement results.

about eight times (8x) greater than with CMSX-10. Typically, the CMSX-10 alloy exhibits about a 3x to 5x advantage in creep strength, thereby suggesting the CMSX-4 alloy blades were in a tertiary creep regime while the CMSX-10 alloy blades were still in a primary creep mode. For CMSX-10, the alloy's 30°C strength advantage prevails to about 1100°C, where it's rupture strength begins to approximate CMSX-4, and with long term exposure, is actually lower. From the 1100°C to about 1160°C regime, the CMSX-10 alloy is not as strong as CMSX-4 on the basis of rupture. The longer the exposure at temperatures within this regime, the greater the alloy's debit, due to the propensity for TCP phase formation within the banded range of temperature. However, for creep-rupture tests above 1160°C, CMSX-10 alloy is again superior to CMSX-4. Moreover, metallographic review of samples tested to rupture at 1200°C reveals extremely good γ' particle stability after 400 hours of exposure.

The CMSX-10 alloy 1% creep-strength is compared to the respective CMSX-4, CM 186 LC and CM 247 LC capabilities in Figure 9. Unlike the alloy's rupture characteristics, CMSX-10 is shown to provide greater 1% creep strength than CMSX-4 throughout the temperature range typically of interest for turbine designers, in tests taken to about 1000 hours duration. This dynamic changes at certain temperatures, though, with longer term tests.

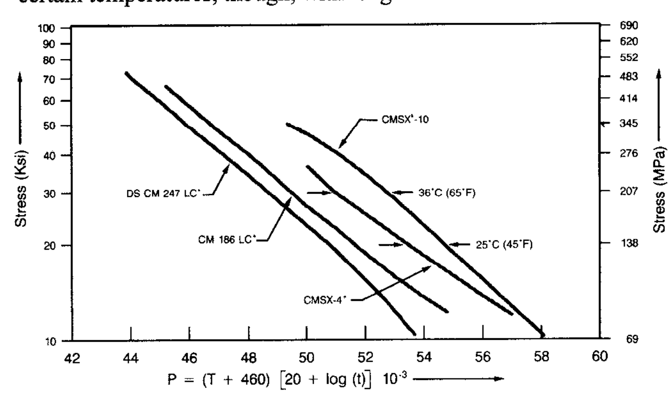


Figure 9: 1.0% Larson-Miller creep strength of several alloys.

The TTT diagram presented in Fig. 2 also illustrates that TCP phase forms relatively sluggishly in the CMSX-10 alloy system at 980°C and below. In this temperature region, the CMSX-10 alloy maintains it's 30°C advantage over CMSX-4 for extremely long duration. For this reason, the alloy is also of considerable interest to land-based industrial turbine producers whose predominating hot section blade component exposure temperatures are around 950°C and below. Like the turbine efficiency improvements realized through CMSX-10 aero-turbine application, some industrial turbine producers anticipate significant turbine efficiency gains with CMSX-10 alloy employment through the reduction of cooling air requirements and/or the increased component stressing which the alloy is able to endure. Such efficiency improvements are extremely desirable since it is reported that an increase of a single percentage point of efficiency can reduce operating costs by $15-20 million over the life of a typical gas-fired combined-cycle plant in the 400-500 megawatt range (28).

Industrial turbine producers require long-term creep-rupture data to accurately predict a material's performance within their turbines. To this end, significant numbers of creep-rupture tests have been completed with the CMSX-10 alloy to about 4000-4500 hours duration. Additional testing is underway, with many anticipated to reach at least 7000 hour lives, while others are planned which will achieve 15,000 hour lives.

For specimens which have ruptured, log-log plots of the "long-term" creep results are presented. While Fig. 10 presents the 982°C rupture strength of CMSX-10 in comparison to the CMSX-4, DS CM 247 LC and IN 738 LC alloys, Figure 11 presents the alloy's 1% creep strength at 982°C, and Figure 12 illustrates the CMSX-10 alloy strength for exposure temperatures ranging from 913 to 1010°C, and lives approaching 4500 hours. Generally, the CMSX-10 alloy develops significantly greater strength than CMSX-4 in these test conditions. However, at 982°C, the CMSX-10 benefit appears to narrow slightly with longer term exposures. This suggests

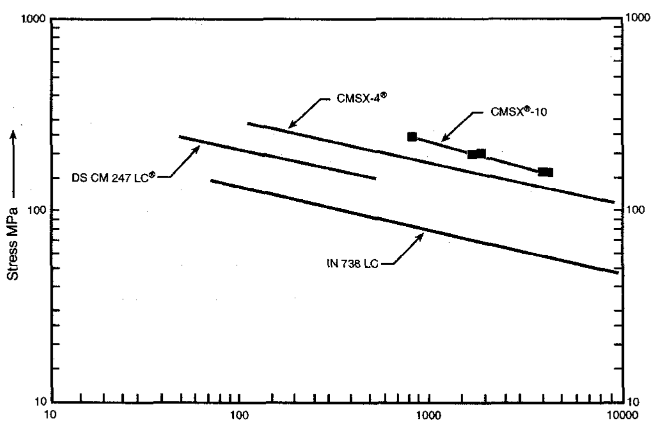


Figure 10: 982°C stress-rupture strength of several alloys.

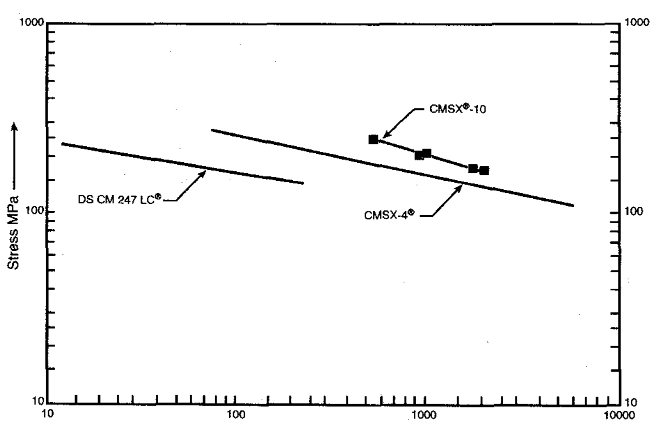
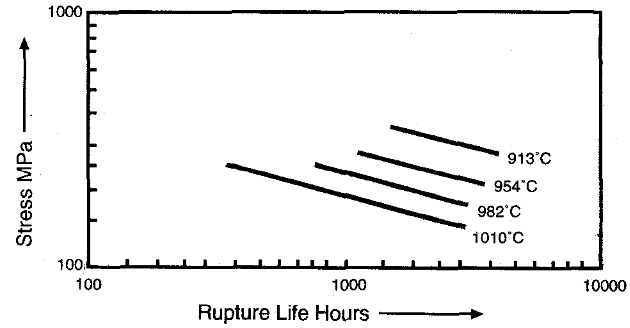
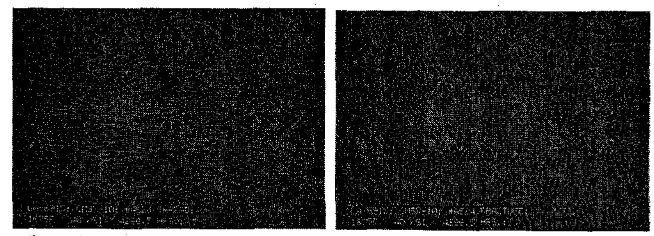


Figure 11: 982°C 1% creep strength of several alloys.

that a point exists where the alloy doesn't provide any benefit relative to CMSX-4. As the narrowing improvement with longer times is a function of alloy TCP phase formation, it must also be noted that the CMSX-4 alloy also forms sigma at such temperatures. The crossover point in alloy capability may not be as early as initially thought, ie. the alloys may not reach parity at 982°C until 20,000 hour exposures occur, rather than 10,000 - 12,000 hours. Longer term creep-rupture tests will investigate the issue.





Thread Section 10μm   Fracture Section 10μm

913°C/275.8 MPa/4296.5Hr. Life Post-test specimen microstructure.

Figure 12: 913-1010°C stress-rupture strength of CMSX-10.

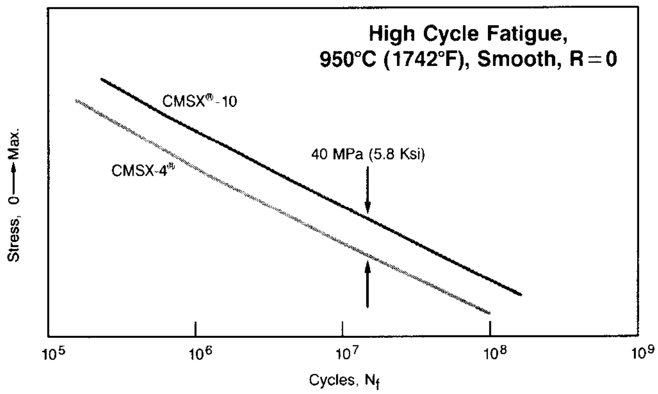
The same situation prevails with the alloy's 1% creep strength at 982°C. Although the TCP phase formation in CMSX-10 at 982°C is quite sluggish, it nonetheless does occur. Similarly, future tests will investigate the issue.

Tests performed at 954°C have run to about 4000 hours, while those performed at 913°C have run to about 4300 hours. Metallographic review of the failed rupture specimens reveal a slight amount of TCP phase forming in the 954°C tested specimen at 4000 hours, while no TCP is apparent in the 4300 hour, 913°C tested specimens.

Longer term creep-rupture tests are underway, all of which have realized at least 5800 hours exposure. The tests which are running at various stress conditions at temperatures ranging from 850°C to 1050°C, currently exhibit creep strains ranging from .03 to 3.0%, respectively suggesting likely rupture lives ranging from 7000 to 10000 hours. Additional tests slated for near-term commencement will explore the alloy's 15000 hour life characteristics at similar temperature ranges. The results of the current and future long-term creep tests are expected to reaffirm the alloy's significant strength advantage over the CMSX-4 alloy at temperatures of 982°C and below; a regime which is quite significant to the land-based power generating gas turbine engine community.

The alloy's high level of Re also positively influences fatigue properties. References 29 and 30 presented the results of LCF and HCF tests undertaken at various temperatures. Generally, the CMSX-10 alloy fatigue performance is at least as good as CMSX-4, and with some test conditions, 2-3 x better. For 50,000 cycle smooth

LCF, CMSX-10 performs similar to CMSX-4 at 700°C, however between 800-950°C, it exhibits a 30°C advantage, or 2.5 x improvement based on life or a 15% advantage based on strength. Notched LCF (K_t=2) tests at 950°C reveal similar results for the two alloys, while those undertaken at 750°C exhibit a 2.5 x advantage for CMSX-10. HCF comparative tests performed at 550°C and 950°C also reveal a 2.5 x improvement (See Fig. 13).



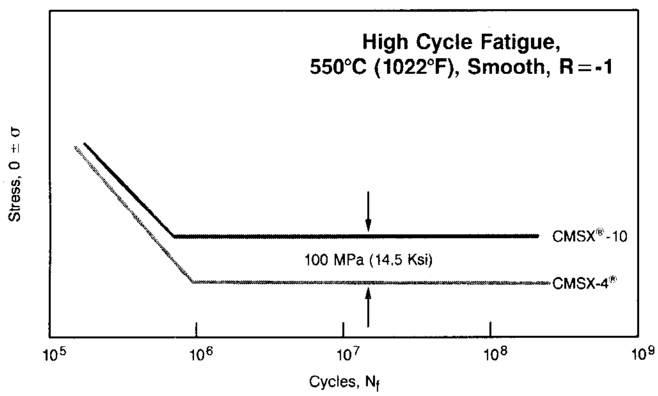


Figure 13: High cycle fatigue behavior of CMSX-10 and CMSX-4 at 550°C and 950°C.

Higher Strength CMSX-10 Derivatives

As the need for higher strength alloys continues, a higher strength derivative of the CMSX-10 alloy has been defined. The alloy currently designated CMSX-10+, exhibits about an 8°C improvement relative to CMSX-10. It continues to exhibit a tendency for TCP phase formation at high temperatures with long exposure, however, applications having service profiles able to accommodate such characteristics have been defined.

While creep-rupture properties are improved, alloy fatigue properties are similarly influenced through the chemistry modification. As greater refractory element levels are employed in the alloy design, alloy Cr and Co level adjustments required for stability jeopardized the derivative alloy's hot corrosion characteristics. However, similar tests to those previously defined for CMSX-10, show acceptable alloy hot corrosion resistance prevails.

The CMSX-10+ material is still in the process of characterization. Comparative creep-rupture test results show that the alloy generally develops about 1.3x - 1.7x greater creep and stress-rupture strengths than CMSX-10 in short-term tests, while longer term characterization (greater than 1000 hours) suggests improvements to 1.5x for tests performed at 1010°C and below. The derivative alloy does not offer significant improvements with long-term test conditions above 1010°C. Further alloy characterization is anticipated to continue through eventual gas turbine engine application.

Environmental Issues

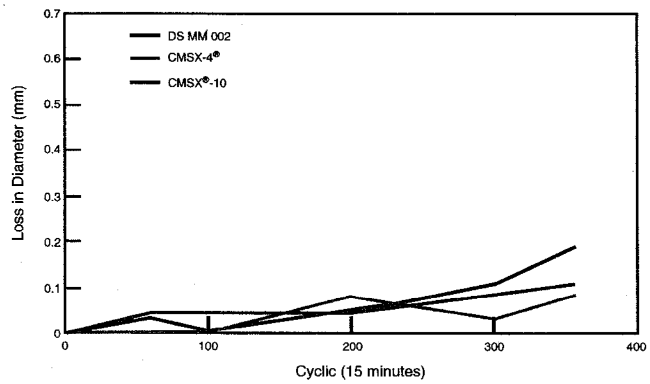
Alloys designed for high temperature operation generally contain a fairly high Al + Ti content. Today, with it recognized that Ti alloying makes the attainment of adequate alloy solution heat treatment more difficult, most new alloys rely more on Al content for γ' formation than Ti. Due to the higher level of Al thereby utilized, most of today's advanced materials exhibit relatively good oxidation resistance characteristics. Furthermore, industry investigations into the positive effect that rare earth elemental addition to superalloys provide, e.g., Y, La and Ce, is helping make the necessary superalloy oxidation characteristics easier to achieve.

For CMSX-10, Figs. 14a and 14b present the comparative results of salt enhanced oxidation testing performed at 1030°C and 1100°C under MACH 0.4 gas stream conditions. At the lower temperature, all alloys investigated provide similar results, however at 1100°C, only the CMSX-10 and CMSX-4 alloys perform similarly; with both significantly better than MM 002.

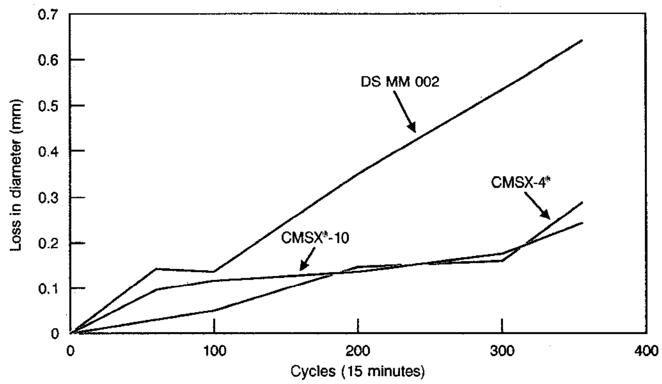
Since most high strength superalloy derivatives necessarily employ lower Cr content, most industry metallurgists intuitively expect third generation SX alloys to exhibit extremely poor hot corrosion resistance. But as shown in Fig. 14c, the CMSX-10 950°C, 2 ppm salt injected, MACH 0.4 hot corrosion resistance is similar to CMSX-4 and, as with the 1100°C comparative alloy oxidation test results, is much better than the MM 002 alloy corrosion resistance.

Until low sulfur, rare earth addition technology matures within the superalloy industry, all hot section blade and vane components will continue to require the application of protective coatings. For CMSX-10, the initial component application employed a plain aluminide coating. The relatively low temperature, high activity coating application provides acceptable coating lives (MM002, CMSX-4 level) without the occurrence of any TCP within the substrate/coating interface zone. Figure 15 illustrates the CMSX-10 alloy in the as-coated and test-soaked conditions. Such coatings are successfully applied to CMSX-10 through pack and chemical-vapor-deposition processes.

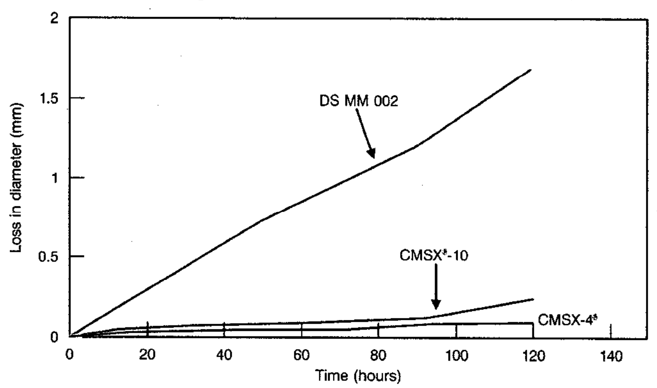
Pt aluminides are also applied to CMSX-10 successfully. Although not as straight-forward as aluminides, today's refined experimental process methods result in the attainment of Pt aluminide coatings which similarly do not cause the formation of TCP phase in the coating/substrate region.



a 1030°C burner rig oxidation

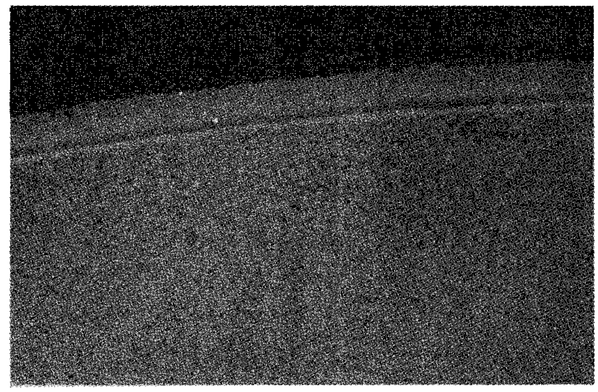


b 1100°C burner rig oxidation

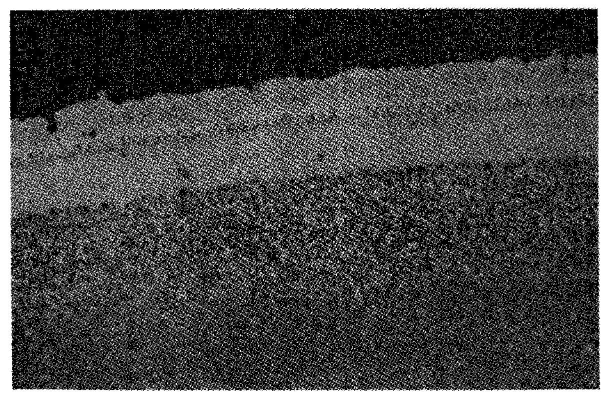


c 950°C burner rig hot corrosion

Figure 14: (a,b) Cyclic bare oxidation of three alloys at 1030°C and 1100°C, 0.25 ppm salt ingestion, and Mach 0.4. (c) Isothermal bare alloy burner rig corrosion of the alloys at 950°C, 2 ppm salt ingestion, and Mach 0.4 gas stream velocity.



As coated. .50μm

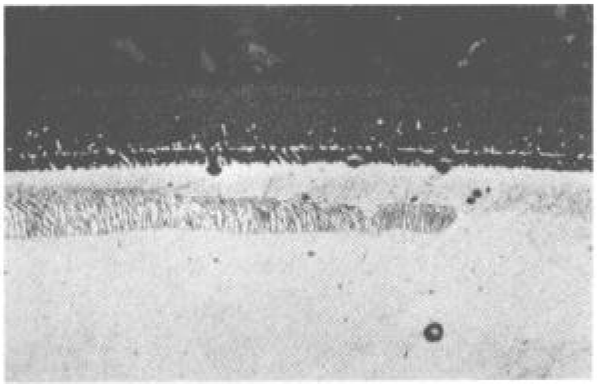


Soaked 150 hrs. at 1100°C. .50μm
No needles.

Figure 15: CMSX-10 alloy aluminide coated specimens. No TCP phase present following a 150 hour soak in static air at 1100°C.

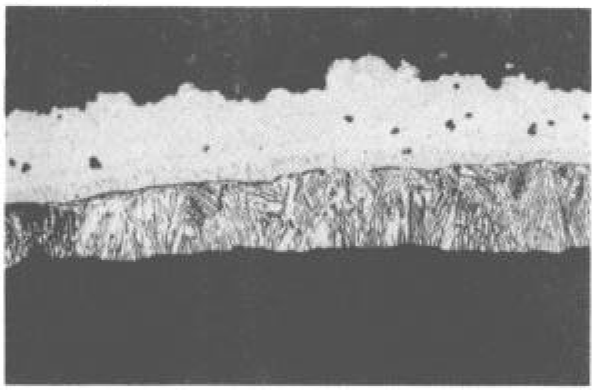
This has not always been the case, though. As Fig. 16 illustrates, the results experienced with early Pt aluminde trials were not acceptable since significant needle phase formed in the CMSX-10 substrate following exposure at 1080°C for 100 hours. Similar results prevailed with CoNiCrAlY overlay coatings, but with much greater needle zone formation (Fig. 16).

Subsequent experimental coating process modifications resulted in satisfactory Pt aluminide coating performance, as shown in Figure 17 where the early, standard Pt aluminide result is compared to the refined process result. Further CoNiCrAlY investigations have not occurred.



.50μm

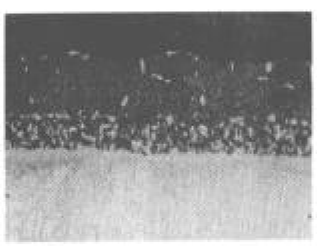
Standard Pt aluminide coating.
Soaked for 100 hrs. at 1080°C.
Needle phase present in 10% of specimen perimeter.



.50μm

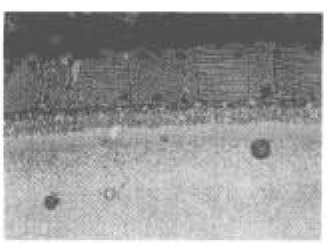
CoNiCrAlY overlay coating.
Soaked for 50 hrs. at 1100°C.
Continuous needle zone under coating.

Figure 16: Standard Pt Aluminide and CoNiCr AlY overlay coatings on CMSX-10.



.20μm

Standard Pt aluminide.
Soaked 100 hrs. at 1100°C.
Extensive TCP phase region around entire specimen perimeter.



.20μm

Experimental Pt aluminide.
Soaked 100 hrs. at 1100°C.
No significant TCP phase.

Figure 17: Standard and experimental Pt aluminide performance on the CMSX-10 alloy.

Summary

The CMSX-10 alloy is flight engine qualified and is a production status material exhibiting extremely good foundry functionality, heat treatment characteristics, high strength, environmental properties and coatability.

The alloy exhibits about 30°C greater creep and fatigue strengths than CMSX-4, particularly in 1000-2000 hour testing up to about 1100°C. For longer term exposures, such as those of interest to industrial turbine designers, the 30°C advantage is most prevalent at temperatures below 950-980°C. It's castability is similar to that associated with CMSX-4 while bare alloy hot corrosion and oxidation resistance is also similar to CMSX-4. Properly applied plain aluminide and Pt aluminide coatings perform well on the alloy system.

A higher strength CMSX-10 derivative is defined and continues under development.

The CMSX-10 alloy is utilized in at least two turbine engine applications while others are expected to be realized within the next two years.

Acknowledgement

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