ADVANCED NI-BASE SUPERALLOYS FOR SMALL GAS TURBINES

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ABSTRACT

Ni-base superalloy cast materials provide an outstanding balance of high temperature strength, fatigue resistance, oxidation resistance and coating performance and can be produced to very tight tolerances in extremely complex configurations, such as axial and centrifugal integral cast turbine wheels. As a result, cast superalloys are used in the most demanding applications of aero and industrial gas turbine engines. Use of these materials is expanding to smaller microturbine, turbojet, turbocharger and missile engine applications due to this unique combination of desirable properties. This paper will present an overview of the application of investment cast Ni-base superalloys and process capability to small turbine and missile engines.

INTRODUCTION

Nickel-base superalloy materials have extensive application in the hot turbine section of aero and industrial gas turbine engines. Traditionally, hot section gas turbine alloy development starts with engine requirements that cannot be met by existing alloys, e.g., higher temperature, strength, or durability requirements. Cast Ni-base superalloys provide a unique combination of characteristics suitable to these requirements, which are also applicable to small turbine and missile engines.

The superalloys encompass a group of alloys, based on nickel, iron or cobalt, which are utilized structurally at operating temperatures of 538°C (1000°F) or higher. Superalloys exhibit superior elevated temperature properties and are used in applications involving the hottest temperatures and/or highest stresses in the gas turbine, most notably turbine blades (or buckets), vanes (or nozzles), integral wheels, discs and combustion chamber components. In addition to maintaining high strength at operating temperatures approaching 85% of melting point, these materials exhibit good hot corrosion and oxidation resistance required in the gas turbine environment. Also, superalloys can be economically cast into components of complex shapes and/or internal configurations with controlled uniform microstructure.

Superalloys were first introduced into military gas turbine engines during World War II, and the technology has advanced dramatically since that time. Continual incremental materials advances have been introduced with casting process developments and optimized alloys "hop-scotching" one another to advance the overall material capability. These advances include conventionally cast, equiax (EQ) alloys, directionally solidified (DS) and single crystal (SX) cast components. This paper will discuss the characteristics and applications of each casting technology, along with examples of alloys and properties.

CASTING PROCESS DEVELOPMENT

Figure 1. Casting Technology Progression [Courtesy GE Power Generation and Alcoa Howmet]

The initial applications of cast superalloy turbine blades and vanes were conventional cast, equiax (EQ) alloys. Equiax castings are used in the majority of applications including static and rotating parts, integral wheels and structural components. Property requirements include high temperature creep and fatigue strength, ductility and weldability for both fabrication and repair.

The introduction of directional solidification produced castings with columnar grains parallel to the high stress loading direction of rotating parts (Figure 1)[1]. These castings realized significant gains in creep-rupture strength and LCF life due to the elimination of grain boundaries transverse to the high stress loading axis and reduced microporosity resulting from the slow moving solidification front inherent in DS technology. DS alloys are typically specified for rotating part applications, such as 2nd and 3rd stage turbine blades, where EQ alloys do not provide adequate creep strength.

A further extension of DS casting technology was the introduction of single crystal processes, pioneered by Pratt & Whitney Aircraft [2] which eliminated all grain boundaries and consequently, the need for grain boundary strengthening elements, such as C, B, Hf and Zr. Since these elements are melting point depressants, the temperature capability of SX alloys was significantly improved. Single crystal alloys are used in the most demanding high stress/ high temperature engine applications such as 1st stage turbine blades and vanes and combustor components. The benefits of SX castings include improved creep-rupture, fatigue, oxidation and coating properties, resulting in superior turbine engine performance and durability [2-6]. In addition, single crystal alloys retain a higher fraction of their thick section rupture life as wall thickness is reduced (Figure 2) [7].

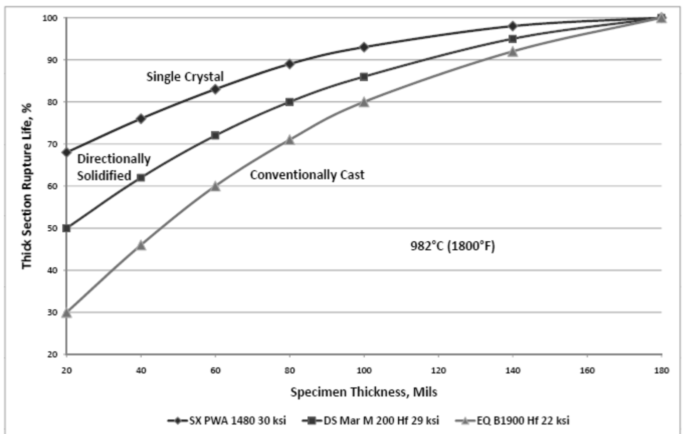

Figure 2. Rupture life vs. specimen thickness showing benefit of SX castings over DS/EQ

ADVANCED SUPERALLOY MATERIALS

Advanced superalloy materials have been introduced to respond to industry needs for improved alloy properties. Equiax alloys CM 939 Weldable®, CM 247 LC® and CM 681 LC®, DS alloys CM 247 LC and CM 186 LC® and SX alloy CMSX-4® are representative of these improvements.

CM 939 Weldable® Alloy

IN 939 alloy (Table 1 [8]) was developed in the late 1960s by the International Nickel Company. This 22% chromium (Cr), hot corrosion resistant alloy has seen wide application in the industrial gas turbine (IGT) market for equiaxed vanes, segments and burner nozzles. However, IN 939 castings are difficult to weld repair due to marginal ductility and associated alloy chemistry design.

Table1 – Nominal chemistry of IN 939 and GTD 222 alloys

Alloy	C	Cr	Co	W	Cb	Ta	Ti	Al	Zr	B	Ni
IN 939	.15	22.5	19	2	1	1.4	3.7	1.9	.10	.01	Bal
GTD 222	.10	22.5	19	2	.8	1	2.3	1.2	.012	.005	Bal

As a result of these difficulties, Cannon-Muskegon developed a modified version of IN 939 alloy for improved repair weldability and mechanical properties, with emphasis on alloy ductility. An optimized aim chemistry was devised with significantly reduced Al, Ti, Ta and Cb (and consequently, lower volume fraction gamma prime phase) compared to standard IN 939, optimized B, Zr and C content and dramatically improved alloy purity for S, P, N, O and Si. This proprietary composition was designated CM 939 Weldable alloy.

Extensive heat treatment and microstructure evaluations were conducted on CM 939 Weldable alloy to evaluate alternative thermal processing. Two heat treatment options emerged as commercially desirable: a five-step production cycle which combines a typical industry multi-stage heat treatment cycle [9] with a coating diffusion cycle, and a simple three step thermal cycle [10] (which also incorporates the coating diffusion step).

Typical microstructures of CM 939 Weldable alloy as-cast and after thermal treatment are shown in Figures 3-4, respectively. Note that minimal eta (η) phase is present in the as-cast microstructure, and there is no eta phase in the heat-treated microstructures. Eta phase, $Ni_3(Ti,Cb,Ta)$, is an undesirable, brittle phase often found in high Ti,Cr,Ta- containing alloys and related to low ductility [11]. High magnification SEM photo micrographs of grain boundary carbide microstructures following heat treatment show fine discrete carbides, which are key to obtaining good alloy strength and ductility (Figure 5) [12].

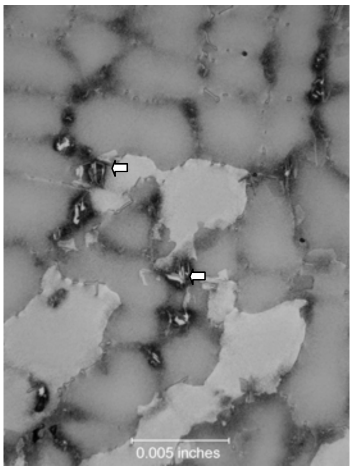

Figure 3 - As-cast CM 939 Weldable showing minimal eta phase (arrows)

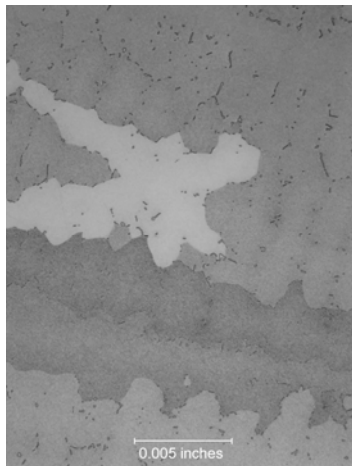

Figure 4 – Microstructure of CM 939 Weldable following heat treatment

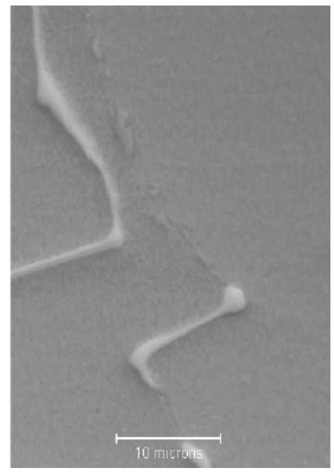

Figure 5 – Fine, discrete grain boundary carbides in CM 939 Weldable after heat treatment

Typical tensile properties for CM 939 Weldable alloy are shown in Table 2; typical stress-rupture properties are presented in Table 3 and Figure 6. Comparative properties for standard IN 939 [13] and GTD 222 [14] alloys are included where available. GTD 222 alloy (Table 1 [15]) is an alternate alloy developed by General Electric Company and often used in similar applications to IN 939 alloy. GTD 222 has improved ductility, but lower strength compared to standard IN 939 alloy.

Analysis of the comparative data shows that CM 939 Weldable has similar strength to IN 939 alloy, with improved ductility and significantly improved strength compared to GTD 222 while maintaining good ductility. In other words, CM 939 Weldable provides the best combination of strength and ductility of the three alloys.

Table 2 – Typical tensile properties

Test Temp	Alloy	0.2% YS (ksi)	UTS (ksi)	Elong. %	RA %
20°C	CM 939 Weldable*	115	166	8	13
	IN 939	121	168	7	9
	GTD 222	97	148	11	14
427°C	CM 939 Weldable	101	139	7	13
593°C	CM 939 Weldable	100	140	7	13
760°C	CM 939 Weldable	98	128	5	10
	IN 939	100	111	2	4
	GTD 222	73	92	5	9
843°C	CM 939 Weldable	82	95	12	19

*Five step thermal cycle

Table 3 – Typical stress-rupture properties

Test Condition	Alloy	Rupture Life, hrs	Elong. %	RA %
816C/172 MPa	CM 939 Weldable*	10796	2	2
816C/207 MPa	CM 939 Weldable	5496	3	3
	GTD 222	1510	6	13
871C/186 MPa	CM 939 Weldable	746	5	8
	IN 939	645	5	5
899C/103 MPa	CM 939 Weldable	3079	3	5
899C/138 MPa	CM 939 Weldable	886	6	7
	GTD 222	235	8	13
899C/172 MPa	CM 939 Weldable	354	8	14
	IN 939	214	4	4
	GTD 222	45	14	34
899C/207 MPa	CM 939 Weldable	130	8	13
899C/234 MPa	CM 939 Weldable	62	8	13

* Five step thermal cycle

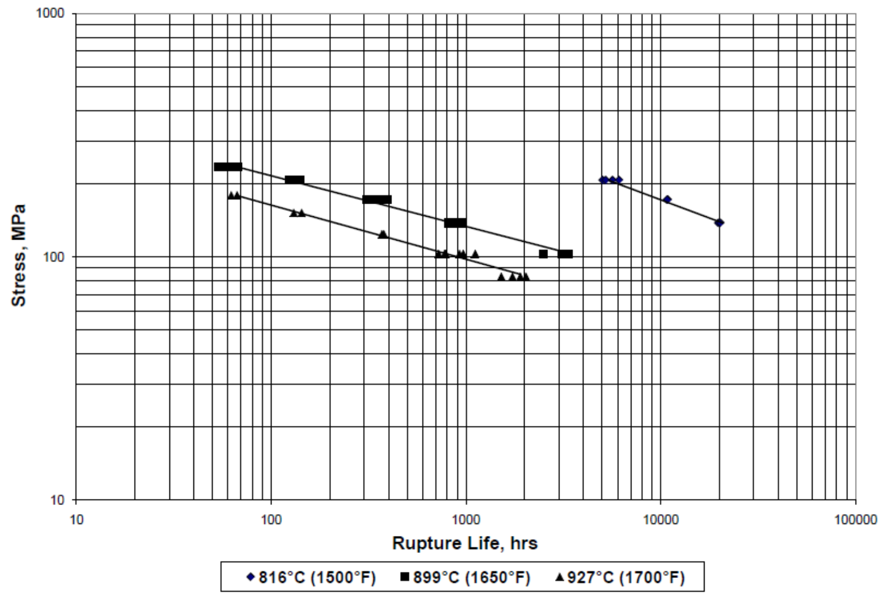

Figure 6 – CM 939 Weldable stress-rupture life (five step thermal treatment)

As an alternative, the three step thermal cycle is shorter, less complex and therefore less expensive post-cast processing. The mechanical property data for this option shows improved strength compared to the five step cycle, with slightly reduced, but still acceptable, ductility. In addition to the overall improvement in rupture life, a significant increase in time to 1% creep has been observed with this thermal treatment [16].

The improved ductility and weldability of CM 939 Weldable alloy has been evaluated through a series of trials conducted by TWI Ltd. (Cambridge UK) under a number of pre-weld thermal conditions, including as-cast, overaged and as-heat treated. Good welding practices include a post-cast annealing or overaging procedure prior to welding; alternate conditions were included to correlate the alloy ductility to the occurrence (or non-occurrence) of weld microcracking. Bead on plate welding trials using both Alloy 625, C263 and Haynes 282® alloy filler wire demonstrated no evidence of HAZ cracking in both the as-welded and post weld heat treated condition [17,18]. Typical microstructure is shown in Figure 7. This work along with routine repair welding of cast components at multiple casters (with no indication of cracking problems) confirmed the improved weldability of CM 939 Weldable alloy. Recent development for improved strength capability has resulted in successful production of CM 939 Weldable filler wire, which is commercially available from Polymet Corporation (Cincinnati, OH) and in use for weld repair of CM 939 Weldable castings.

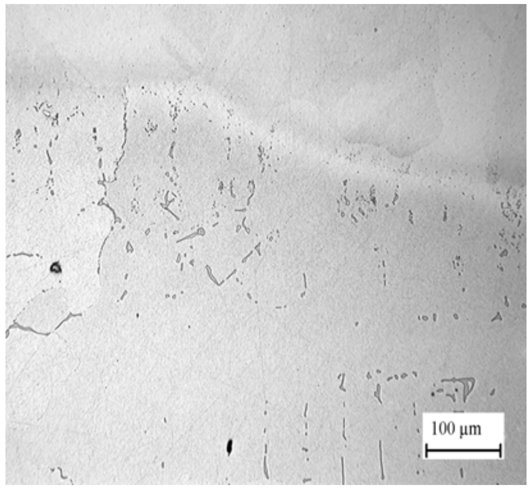

Figure 7 – Typical weld microstructure at the CM 939 Weldable/C263 filler metal fusion line

As a result of the favorable property evaluations, CM 939 Weldable is replacing IN 738 LC and IN 713 LC alloys for structural components such as combustor and turbine casings and vane rings in small high performance turbojet applications.

CM 247 LC Alloy

Early DS castings were made from equiax blade alloys such as MAR M 002, MAR M 200 and MAR M 247; however, many of these alloys exhibited low ductility and cracking along the DS grain boundaries [19]. This provided the impetus for development of alloys optimized to take advantage of the DS process. CM 247 LC alloy (Table 4) is a modification of MAR M 247 alloy designed to reduce DS grain boundary cracking of thin-walled complex cored castings.

Table 4 – Nominal chemistry of CM 247 LC and Mar M 247 Alloys

Alloy	C	Cr	Co	W	Mo	Ta	Ti	Al	Hf	Zr	B	Ni
CM 247 LC	.07	8.1	9.2	9.5	.5	3.2	.7	5.6	1.4	.007	.015	Bal
MAR M 247	.15	8.4	10	10	.7	3	1	5.5	1.5	.05	.015	Bal

Chemistry modifications for CM 247 LC alloy included reducing Zr and Ti content and tighter control of Si and S which produced improved castability. Reduced C content improved the carbide microstructure, carbide stability and room temperature to intermediate temperature ductility. CM 247 LC alloy shows a 2x improvement in ductility compared to standard MAR M 247 alloy. W, Mo and Cr content were reduced to compensate for lower C to balance the alloy for Phacomp considerations [19]. These changes were also beneficial to equiax castings, resulting in less hot tearing & hot cracking; consequently, CM 247 LC alloy has also been selected for many EQ applications, such as axial and centrifugal integral wheels, turbine blades and vane segments.

Re-bearing Alloys

The next significant advance in alloy development was the introduction of rhenium (Re) to EQ, DS and SX alloys (Table 5). These so-called "second generation" alloys possess significant improvement in creep-rupture properties due to Re which partitions to the γ matrix, retards coarsening of the γ' (strengthening) phase and increases the γ/γ' misfit [20]. Re "clusters" act as obstacles to dislocation movement resulting in improved alloy strength.

Table 5 – Nominal chemistry of Re-bearing alloys

Alloy	C	Cr	Co	W	Re	Ta	Mo	Al	Ti	Hf	Zr	B	Ni
CM 681 LC (EQ)	.11	5.5	9.3	8.4	3	6.1	.5	5.7	.15	1.5	.013	.018	Bal
CM 186 LC (DS/SX)	.07	6	9	8	3	3	.5	5.7	.7	1.4	.005	.015	Bal
CMSX-4 (SX)		6.5	9.6	6.4	3	6.5	.6	5.6	1	.10			Bal

CM 681 LC Alloy

Cannon-Muskegon developed CM 681 LC alloy for application as a high performance integral cast turbine wheel alloy. This alloy is an oxidation resistant alumina former, with relatively high Ta, low Ti, 3% Re and 1.5% Hf (Table 5). CM 681 LC was evaluated as part of an Advanced Materials for Small Turbine Engines (AMSTE) team NASA Aerospace Industry Technology Program (AITP) project which confirmed foundry performance in terms of low susceptibility to hot tearing/hot cracking and integral wheel quality assessment [21].

Typical room temperature tensile properties of CM 681 LC alloy vs. EQ MAR M 247 and EQ CM 247 LC alloys are provided in Table 6 demonstrating improved strength with good ductility. A comparison of CM 681 LC and MAR M 247 rupture life is shown in Figure 8.

Table 6 – Typical room temperature tensile properties

Alloy	0.2% YS (MPa)	UTS (MPa)	Elong. %	RA %
CM 681 LC [DA]*	890	1124	7	9
MAR M 247 [MFW]	814	848	5	10
CM 247 LC [Aged]**	779	834	9	16

* 2 hrs/1083°C GFQ + 20 hrs/871°C GFQ
** As-cast + 20 hrs/871°C AC

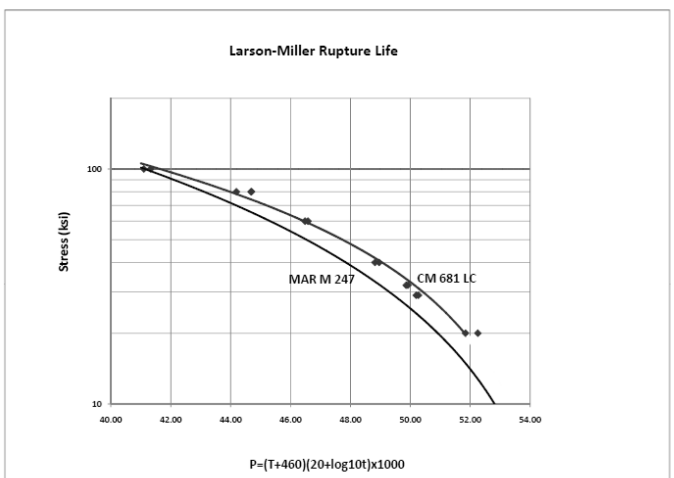

Figure 8 – CM 681 LC/MAR M 247 comparative Larson-Miller rupture life

Applications developed or envisaged for CM 681 LC alloy include cost effective, high performance integral cast axial turbine wheels for cruise missile, UAV, and APU turbine engines, and microturbines for distributed power. Radial turbine wheel applications are also under development.

CM 186 LC Alloy

CM 186 LC® is a Re-bearing DS alloy (Table 5) with mechanical properties close to those of first generation (non Re-bearing) SX superalloys. The excellent castability developed for DS CM 247 LC alloy was preserved and CM 186 LC alloy can be used in the as cast + double aged condition, reducing manufacturing costs and preventing the formation of solution heat treatment induced recrystallization (RX) defects [22].

As shown in Fig. 9, Larson-Miller rupture life of CM 186 LC alloy is equivalent to first generation SX alloys CMSX-2/3 under creep/stress-rupture test conditions which correspond to 982°C (1800°F). Strength at higher temperatures is intermediate between DS CM 247 LC and CMSX-2/3 [22].

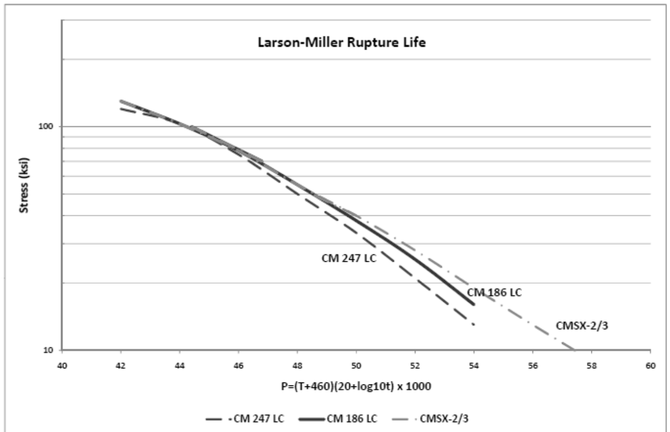

Figure 9 – Larson-Miller stress rupture life of DS CM 186 LC, DS CM 247 LC and SX CMSX-2/3

In recent years, the benefits of SX technology (enhanced component life due to superior fatigue, creep, oxidation and coating performance) have sometimes been offset by lower casting yields due to the complexity of casting features. Since all grain boundary strengthening elements have been eliminated, there is very little tolerance for casting anomalies, such as low and high angle boundaries (LAB/HAB). Typical SX castings limit LAB defects to 6-8.5° in the highest stressed locations of the castings.

DS Re-bearing alloys (such as CM 186 LC) have at times been used to replace first generation SX alloys (such as CMSX-2/3) at a cost savings due to higher casting yields [3]. However, DS components are less advantageous than SX vane castings due to grain boundaries in non-airfoil regions, particularly the inner and outer shrouds of multiple airfoil segments. Consequently, the concept to SX-cast CM 186 LC alloy to produce a single crystal casting with a more generous grain specification was evaluated with the intent of relaxing the grain requirements for higher casting yield [23]. This has been successfully implemented in the Rolls-Royce AE3007 and AE1107C Liberty 2nd vane segment with 35 million hours/flight cycle engine experience, with component lives typically 20,000 hours/cycles (Figure 10).

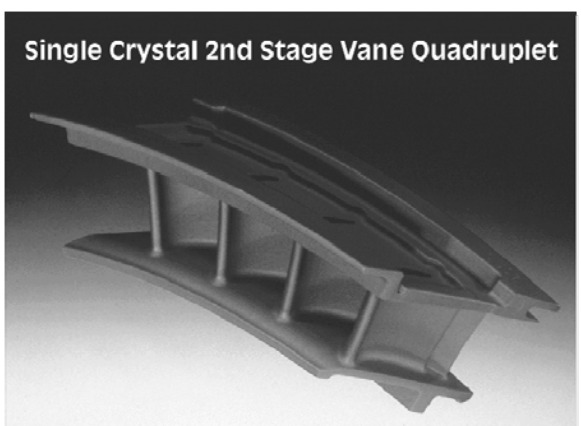

Figure 10 – AE 3007 A1 2nd vane segment cast in SX CM 186 LC alloy

CMSX-4 Alloy

CMSX-4 is a second generation, Re-bearing nickel-base SX superalloy which has been extensively investigated and documented in the literature [4,5,22,24-25]. The nominal chemistry is provided in Table 5. CMSX-4 alloy has been successfully used in numerous aero and industrial gas turbine applications since 1991. These applications, such as high pressure turbine blades and seals, have demonstrated an impressive combination of high temperature strength, good phase stability and oxidation, hot corrosion and coating performance in extensive engine service [26-28]. Close to ten million pounds (1200 heats) of CMSX-4 alloy have been manufactured to date.

CMSX-4 [La+Y] alloy was subsequently introduced to meet ever-increasing engine design requirements for hot section turbine components. Of particular interest was improvement in bare alloy oxidation performance to minimize blade tip and internal oxidation and improve thermal barrier coating (TBC) adherence. Evaluation of reactive element additions demonstrated the oxidation behavior of bare CMSX-4 alloy (sulfur content ≤2 ppm) could be dramatically improved by the addition of lanthanum (La) and yttrium (Y) (Figure 11) [29]. These reactive elements tie up the sulfur and phosphorous as stable sulfides/phosphides which has a beneficial effect on the adherence of the alumina scale.

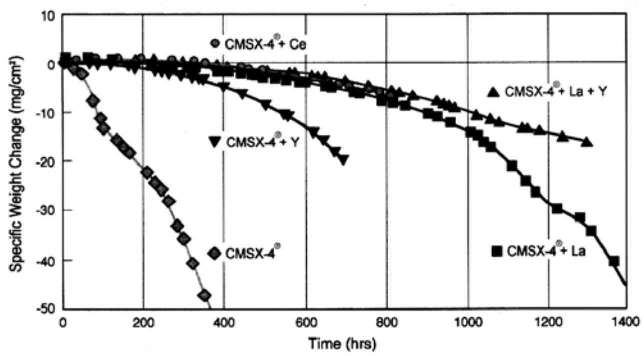

Figure 11 – 1093°C (2000°F) dynamic cyclic oxidation results for bare CMSX-4 alloy with and without reactive element additions

An example of the benefit of La + Y additions is shown in the remarkable surface microstructure observed following creep-rupture testing at 1050°C (1922°F) (Figure 12) [30]. After 1389 hours there was an 8 micron thick, 2-layer oxide film and no evidence of gamma prime depletion at all. Without the La+Y addition, significant γ' depletion would be expected from extended exposure at this temperature. This behavior translates to substantial improvement to EB-PVD TBC life, as demonstrated in Figure 13 [31].

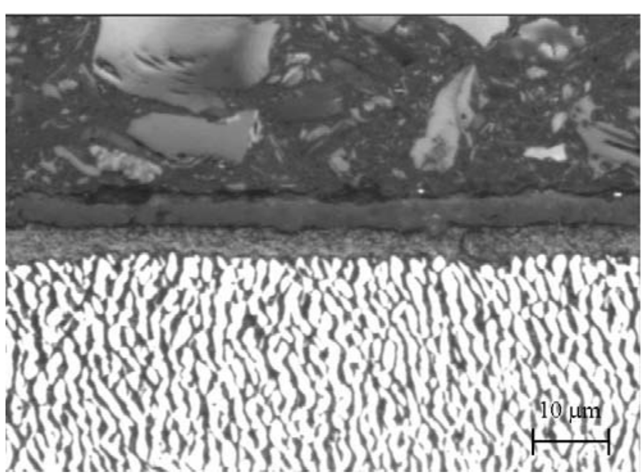

Figure 12 – Surface microstructure on CMSX-4 [39 ppm La+Y] following creep-rupture testing at 105°0C/125 MPa (courtesy Rolls-Royce plc)

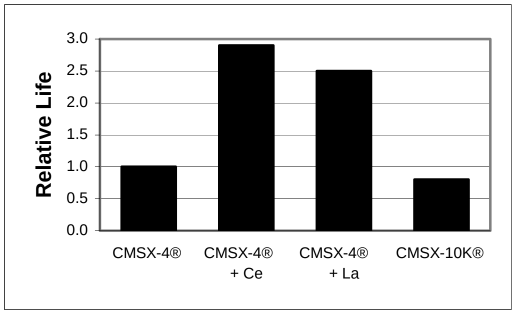

Figure 13 – Reactive element effects on EB-PVD TBC life
1093°C/10 hr thermal exposure cycles (courtesy Solar® Turbines)

CMSX-4(SLS)[La+Y] alloy is an improved version of CMSX-4 which is pre-alloyed with La and Y and has consistent low sulfur content of 1 ppm. Casting trials with pre-alloyed CMSX-4(SLS)[La+Y] ingot have demonstrated improved control and retention of La+Y content compared to traditional Ni-foil-wrapped add packets attached to the charge increment at the casting furnace. The effectiveness of add packets is dependent upon melt-in and subsequent induction stirring prior to pour. Pre-alloying the ingot provides greater consistency of the reactive additions within the molten alloy and reduces the hold time at temperature needed to tie up the residual sulfur, minimizing reactive element loss during remelt. In addition, due to the consistent, low sulfur content of CMSX-4(SLS)[La+Y], smaller La+Y retentions are needed to obtain the same superior bare oxidation properties and coating/TBC life [32].

CMSX-4 alloy is ideal for small solid uncooled parts in the hottest applications of missile & small turbine engines. CMSX-4(SLS)[La+Y] offers improved oxidation resistance for bare alloy and/or coated conditions.

SUMMARY

Ni-base cast superalloys offer an outstanding combination of properties and performance which are desirable for small microturbine, turbojet, turbocharger and missile engine components. Representative properties and applications for equiaxed, directionally solidified and single crystal cast components have been discussed. The potential benefits include improved temperature capability and durability, along with economical manufacture of complex configurations for these engine programs.

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30. Courtesy Rolls-Royce plc Internal Data (Private)
31. Courtesy SOLAR® Turbines Internal Data
32. K. Harris and J.B. Wahl, “Improved Single Crystal Superalloys, CMSX-4®(SLS)[La+Y] and CMSX-486®”, *Superalloys 2004*, (Warrendale, PA: TMS, 2004), 45-52.