RECENT ADVANCES IN CAST SUPERALLOYS

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BACKGROUND

There is a continuing and strengthening demand for advanced gas turbines with lower fuel burn and commensurate reduced CO_2 exhaust emissions. Little evidence points to future lower aviation kerosene costs for flight engines. Particularly in the U.S.A., lower cost 'fractured" natural gas is assisting the running of large combined – cycle industrial gas turbines for base load, relatively clean, electricity generation.

These requirements have led to the development of new cast superalloys or increased usage of relatively recently developed alloys, both equiaxed (EQ) and single crystal (SX) compositions.

EQUIAXED ALLOYS

Work is current to develop a cast version of 718 Plus® alloy, which along with RS 5 alloy, are designed for cast structural components having stressed temperature capability of up to 1300°F (704°C) compared to the widely used IN 718 alloy with its 1200°F (649°C) maximum use temperature.

718 Plus® is unusual in that it has a deliberate phosphorus (P) chemistry range, necessitating CM to develop on-stream (during VIM alloy production) P analytical capability at the modest ppm level, using the latest PAN Axios Fast PW 4600 XRF equipment, using standards with ppm accurate P determinations by ICP-MS (Perkin Elmer NexION™ 300 Q) equipment. It is critical that both these EQ alloys can be structurally weld repaired/weld fabricated using the parent alloy as filler metal. Restraint weld conditions during fabrication can be encountered.

CM 939 Weldable® has now amassed several million hours of IGT vane operating experience, with component lives exceeding 50,000 hrs. The alloy has similar high temperature strength to Rene' 77 and C 1023 alloys, but is readily structurally weld repairable using the parent alloy or slight modifications, for increased casting yield and component turbine life extension. It is capable of operating at metal temperatures of 1600-1650°F (871-900°C).

SINGLE CRYSTAL ALLOYS

Relatively high strength 1.5% Re containing alloys have been developed with appreciable turbine applications to date, in particular Rene' N-515 alloy (1). CM has developed CMSX®-8 (1.5% Re) (2) for flight engines and CMSX®-8 [B/C] (3) for large industrial turbines. CMSX®-8 has high creep and LCF strength, close to that of CMSX-4® (3% Re) (4) alloy, but with improved SX castability and reduced Re content.

Low sulfur (S) (1 ppm S max) versions of established alloys e.g. Rene' N-5 Rene' N-515, PWA 1429, AM 1 (SLS) and CMSX-4® (SLS) have been developed in recent years to improve turbine airfoil gas temperature capability (TBC spallation) and bare and coated oxidation component lifing.

CM has developed a "4^{th} Generation" SX alloy designated CMSX-4® Plus. Its all-round performance e.g. SX castability, mechanical properties, phase stability and environmental properties appear to be excellent.

The creep-rupture properties of the CMSX-4® Plus Mod C chemistry (Table 1, 2 and 3) are quite high. The metal temperature stress-rupture capability advantage of Mod C over standard CMSX-4® is 40°F (22°C) at 1800°F (982°C) and 50°F (28° C) 1.0% creep capability (density corrected) at this temperature. At the 15.0

ksi/2050°F (103 MPa/1121°C) very high temperature test condition, the Mod C is equivalent to CMSX-4® which has very exceptional stress-rupture life at this test condition, but with improved rupture ductility (17 – 28% Elong (4D) and 38 – 39% RA) compared to CMSX-4®.

Remarkably the density corrected creep-rupture properties of Mod C at 36.0 ksi/1800°F (248 MPa/982°C) are close to that of CMSX-10K® (6.3% Re) and superior at 15.0 ksi/2050°F (103 MPa/1121°C). (Table 4).

Table 1

CMSX-4® Plus (SLS) Alloy

Currently finishing development by CM – initial V-5 400 lb (180 kgs) heats

5V0603 (MOD A) and **5V0636 (MOD B)** and **5V0660 (MOD C)**

Stress-Rupture Properties [DL 10s RR Corpn., SMP SX Bars]

Life (hrs)

	CMSX-4® Plus			CMSX-4®	CMSX®-8
	MOD A	**MOD B**	**MOD C**		
651 MPa/850°C (94.4 ksi/1562°F)	190 hrs	224 hrs		160 hrs	142 hrs
517 MPa/871°C (75.0 ksi/1600°F)	635 Hrs	819 hrs		335 hrs	418 hrs
517 MPa/913°C (75.0 ksi/1675°F)		128 hrs	216 hrs	52 hrs	67 hrs
390 MPa/950°C (56.6 ksi/1742°F)	198 hrs	202 hrs		70 hrs	103 hrs
248 MPa/982°C (36.0 ksi/1800°F)	398 hrs	493 hrs	615 hrs	275 hrs	236 hrs
276 MPa/982°C (40.0 ksi/1800°F)	225 hrs	299 hrs		141 hrs	144 hrs
296 MPa/982°C (43.0 ksi/1800°F)		200 hrs	276 hrs	88 hrs	89 hrs
248 MPa/1010°C (36.0 ksi/1850°F)	139 hrs	169 hrs	227 hrs	82 hrs	85 hrs
190 MPa/1050°C (27.6 ksi/1922°F)	143 hrs	184 hrs	231 hrs	90 hrs	81 hrs
103 MPa/1121°C (15.0 KSI/2050°F)	369 hrs	502 hrs	662 hrs	640 hrs	293 hrs

Table 2

CMSX-4® Plus (SLS) Alloy

Currently finishing development by CM – initial V-5 400 lb (180 kgs) heats

5V0603 (MOD A) and **5V0636 (MOD B)** and **5V0660 (MOD C)**

Stress-Rupture Properties [DL 10s RR Corpn., SMP SX Bars]

Time to 1.0% Creep (hrs)

	CMSX-4® Plus MOD A	CMSX-4® Plus MOD B	CMSX-4® Plus MOD C	CMSX-4®	CMSX®-8
390 MPa/950°C (56.6 ksi/1742°F)	72 hrs	88 hrs		37 hrs	36 hrs
248 MPa/982°C (36.0 ksi/1800°F)	209 hrs	280 hrs	374 hrs	125 hrs	116 hrs
276 MPa/982°C (40.0 ksi/1800°F)	110 hrs	160 hrs		72 hrs	55 hrs
296 MPa/982°C (43.0 ksi/1800°F)		93 hrs	171 hrs	45 hrs	39 hrs
248 MPa/1010°C (36.0 ksi/1850°F)	73 hrs	89 hrs	130 hrs	35 hrs	40 hrs
190 MPa/1050°C (27.6 ksi/1922°F)	70 hrs	83 hrs	118 hrs	37 hrs	34 hrs

Table 3

CMSX-4® Plus (SLS) Alloy

Currently finishing development by CM – initial V-5 400 lb (180 kgs) heats

5V0603 (MOD A) and **5V0636 (MOD B)** and **5V0660 (MOD C)**

Stress-Rupture Properties [DL 10s RR Corpn., SMP SX Bars]

Initial Creep Properties

Time to 2.0% Creep (hrs)

	CMSX-4® Plus MOD A	CMSX-4® Plus MOD B	CMSX-4® Plus MOD C	CMSX-4®	CMSX®-8
390 MPa/950°C (56.6 ksi/1742°F)		121 hrs		-	50 hrs
248 MPa/982°C (36.0 ksi/1800°F)	243 hrs	320 hrs	416 hrs	160 hrs	136 hrs
276 MPa/982°C (40.0 ksi/1800°F)	134 hrs	190 hrs		-	79 hrs
248 MPa/1010°C (36.0 ksi/1850°F)	85 hrs	103 hrs	147 hrs	45 hrs	48 hrs
190 MPa/1050°C (27.6 ksi/1922°F)	87 hrs	110 hrs	138 hrs	54 hrs	43 hrs

Table 4

CMSX-4® Plus (SLS) Mod C

The creep-rupture properties of the above alloy are quite close to that of CMSX-10K® [6.3% Re] – see table below (not density corrected).

Based on typical average properties:-

		Time to Rupture	Time to 1% Creep	Time to 2% Creep
248 MPa/982°C (36.0 ksi/1800°F)	CMSX-4® Plus Mod C (5V0660)	615 hrs	374 hrs	416 hrs
	CMSX-10K®	718 hrs	390 hrs	459 hrs
103 MPa/1121°C (15.0 ksi/2050°F)	CMSX-4® Plus Mod C (5V0660)	662 hrs	NA	NA
	CMSX-10K®	558 hrs	NA	NA

The density at RT of CMSX-4® Plus Mod B (5V0636) determined by NPL in the UK is 8.887 kg/dm^3 – see table below for comparison with other SX alloys.

Alloy	Density (RT) kg/dm^3
CMSX-4®	8.70
AM 1	8.59
PWA 1484	8.95
SC 180	8.84
Rene' N-6	8.97
CMSX-10K®	9.05
CMSX-4® Plus Mod B	8.89

References:

(1) P.J. Fink, J.L. Miller, D.G. Konitzer [GE Aviaition] "Rhenium Reduction – Alloy Design Using an Economically Strategic Element," JOM, 62 No. 1 55-57 (Jan 2010).

(2) J.B. Wahl, K. Harris [Cannon-Muskegon] "New Single Crystal Superalloys, CMSX®-7 and CMSX®-8, GT 2014-25155 ASME Turbo Expo 2014, June 16.20 2014, Dusseldorf, Germany.

(3) J.B. Wahl, K. Harris [Cannon-Muskegon] "New SX Superalloys – Overview and Update", European Superalloys and Applications (2^{nd} Symposium), Giens, France, 12-16 May 2014

(4) K.P.L. Fullagar, R.W. Broomfield, M Hulands [Rolls-Royce plc]. K Harris, G.L. Erickson, S.L. Sikkenga [Cannon-Muskegon] "Aero Engine Test Experience with CMSX-4® Alloy Single Crystal Turbine Blades", Trans. ASME Vol. 118 April 1996 pps 380-388. (International Gas Turbine and Aeroengine Congress and Exposition, The Hague, The Netherlands, 13-16 June 1994).