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Current and Future Materials In Advanced Gas Turbine Engines*

G.A. Kool

FUTURE gas turbine engines will have better fuel efficiencies and lower operating costs. This will require new and advanced materials with higher temperature capabilities. This paper discusses some of the presently applied materials in the turbine section of gas turbines, and reviews the material developments that are occurring and will be necessary for the near and long term futures.

Combustor and Exhaust

Both Ni- and Co- base alloys are used in gas turbine combustors and exhaust segments. For the hottest parts like combustion chambers and afterburner liners with metal temperatures up to 1100 °C, the Co-base alloy Haynes 188 has proven its outstanding performance in service for several years. The widely used Co-alloy is a solid solutioning strengthened alloy containing 22% chromium. In general, Co-base alloys have superior thermal fatigue strength and hot corrosion resistance over the Ni-base alloys. Ni-base alloys are stronger at low and intermediate temperatures and have better oxidation resistance when Al is added as an alloying element.

The combustor and afterburner are currently protected by a ceramic coating. These thermal barrier coatings (TBCs) typically consist of an oxidation resistant bond coat and a thermal insulating top coat, both of which are applied by plasma arc spraying. Advanced TBC-systems consist of a dense oxide-free Ni(Co)CrAlY bond coating and a porous 7-8 wt% yttria-stabilized zirconia ZrO_2/Y_2O_3 top coating. Ongoing research will lead to improved oxidation resistance of bond coats and better adherence between substrate and coating (Ref 1-2). Inconel 718 is the most widely used sheet metal for the cooler parts in the combustor and exhaust because of its high strength up to 650 °C, good workability and weldability.

Turbine Blades and Vanes

In Table 1 an overview is given of the chemical composition and high temperature creep performance of superalloys used for turbine blades and vanes. The 100 hr/140 MPa creep rupture strength has increased at an average rate of 10 °C per year from about 1940 to 1980. Specific aero engine fuel consumption has been halved, thrust has been increased 50 fold, and thrust-to-weight ratios have increased by a factor of ten during this period, owing largely to the increases in alloy performance. The alloy performance improvements are significantly pushed by improvements in casting techniques, coatings and internal cooling design (Fig. 1 and 2). Turbine inlet temperatures in military aircraft engines are close to 1580 °C currently, and there is hope for 1700 °C before the turn of this century (Ref 3).

The single crystal airfoils were first cast by Pratt & Whitney in the mid-1960s. Several nickel-based superalloys were especially designed for single crystal casting, such as PWA 1480 and CMSX-2 (USA), SRR99, RR 2000 (GB), AM1 and AM3 (France). The use of such single crystal alloys has led to temperature capabilities of about 80 °C higher than that of conventionally cast polycrystal superalloys such as IN 100. The favorable properties of single crystal alloys in terms of life are given in Fig. 3.

Single crystal PWA 1480 turbine blades first entered service in the JT9D-7R4 engine in 1982, powering the Boeing 767 and Airbus A310, and in military engine applications (Ref 4). The alloying elements in PWA 1480 such as Al, Ti, W and Ta were added to obtain 60 vol. % of γ phase. The alloy PWA 1480 ob-

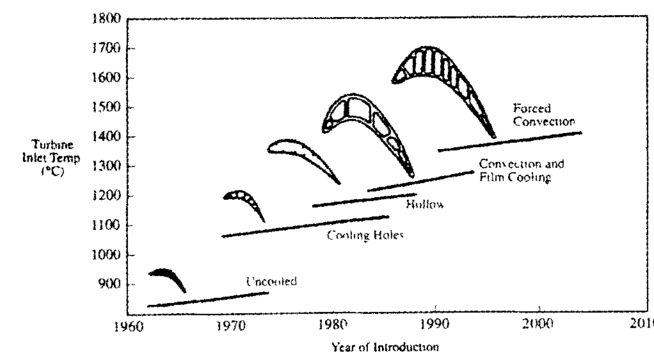

Fig. 1 Evolution in turbine cooling technology (Ref 3).

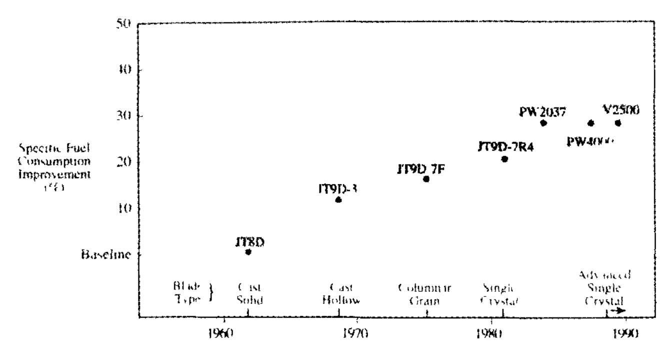

Fig. 2 The improvement in fuel efficiency with engine model and the contributions made by cast superalloy technology (Ref 4)

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G.A. Kool, Materials Department, National Aerospace Laboratory NLR

Table 1 Nominal Compositions of Cast Nickel-Base Superalloys Used in Turbine Blades (Ref 3, 5-7)

Conventionally Cast — Composition in weight percent														
Alloy	**C**	**Cr**	**Co**	**Al**	**Ti**	**Mo**	**W**	**Nb**	**Ta**	**Zr**	**B**	**Other**	**Year#**	**T°(C)[1]**
IN-718	0.05	19	-	0.5	1.0	3.0	-	5.0	-	0 01	0.005	18Fe	1965	700
IN-713C	0 05	12	-	5 9	0.6	4 5	-	2.0	-	0.1	0.010	-	1955	985
IN-100	0.18	10	15	5.5	4.7	3.0	-	-	-	0.05	0 015	1 0V	1958	1000
René 80	0.17	14	9 5	3 0	5.0	4.0	4.0	-	-	0.03	0 015	-	1965	1000
IN-738LC[2]	0.11	16	8.5	3.4	3.4	1 7	2 6	0.9	1.7	0.05	1 010	-	1970	980
IN-939[2]	0.15	22.5	19	1.9	3.7	-	2.0	1.0	1 4	1.1	0 100	-	1973	970
IN-6201[2]	0.03	20	20	2 4	3.6	0.5	2 3	1 0	1 5	0 05	0.800	-	1978	1010
MAR-M 246	0.15	9	10	5.5	1.5	2.5	10	-	1.5	0 05	0.015	-	1966	1025
Directionally Solidified — Composition in weight percent														
Alloy	**C**	**Cr**	**Co**	**Al**	**Ti**	**Mo**	**W**	**Nb**	**Ta**	**Zr**	**B**	**Other**	**Year#**	**T°(C)[1]**
MAR-M200 Hf	0 15	9.0	10	5.0	2.0	-	12 5	1 0	-	0 05	0.02	2 0 Hf	1970	1040
MAR-M002 DS	0.15	9.0	10	5.5	1.5	-	10	-	2.5	0 05	0.015	1 5 Hf	1975	1045
IN-6203[2]	0.15	22	19	2.3	3.5	-	2 0	0 8	1 1	0 1	0.01	0.75 Hf	1981	1020
Single Crystal — Composition in weight percent														
Alloy	**C**	**Cr**	**Co**	**Al**	**Ti**	**Mo**	**W**	**Nb**	**Ta**	**Zr**	**B**	**Other**	**Year#**	**T°(C)[1]**
PWA 1480	-	10	5.0	5.0	1.5	-	4.0	-	12	-	-	-	1980	1060
CM SX-2	-	7.9	4.7	5 5	1.0	0.6	8.0	6.0[3]	-	-	-	-	1980	1070
SRR-99	0.015	8 5	5.0	5.5	2.2	-	9 5	-	2 75	-	-	-	1980	1080
AM 1	-	7 5	6 5	5.2	1 2	2.0	5 5	-	8 6	-	-	-	1985	1090
PWA 1484	-	5.0	10	5 6	-	2 0	6.0	-	8 7	-	-	3 Re 0.1Hf	1986	1100
CM SX-4G	-	6 2	9 5	5.5	1 0	0.6	6 5	6 5[3]	-	-	-	2.9 Re 0.1 Hf	1986	1110
MC 2	-	8 0	5.0	5.0	1 5	2.0	8.0	-	6.0	-	-	-	1990	1125
SC 16[2]	-	16	-	3.5	-	3 0	-	-	3.5	-	-	-	1990	1030

Approximate year of introduction. (1) Temperature capability (100 hr to rupture at 140 Mpa). (2) High chromium alloy suitable for land and marine-based gas turbines. (3) Indicates combines Nb+Ta

tains its excellent oxidation resistance from its high levels of aluminum and tantalum in combination with a coating. Among the developed alloys in France the industrial gas turbine alloy SC 16, aimed to replace IN-736LC, and the aerospace alloy AM1 alloy are worth mentioning (Ref 5-6). The AM1 alloy is now being used in the SNECMA M88 military engine which powers the RAFALE fighter plane (Ref 3).

More recently, second generation nickel based single crystal superalloys have been introduced (Ref 7). The higher strength single crystal alloys, such as CMSX-4 and PWA 1484, were developed in the USA. These two alloys contain 3% rhenium and have a 30 °C use-temperature advantage over first generation single crystal alloys such as PWA 1480. The addition of 3% rhenium provides solid solution strengthening and permits higher Al+Ti contents, which in turn produce a higher volume fraction of γ. Rhenium also reduces the coarsening rate of γ by decreasing the fusion kinetics at the matrix/γ interface. The strongest non-rhenium containing single crystal alloy MC29, developed by ONERA in France, competes with the USA-developed alloys PWA 1484 and CMSX-4.

It should be noted that besides developments in blade materials, leading to the latest single crystal alloys, there have been developments in blade cooling techniques. Most recently there have been developments in single crystal casting to enable the transpiration cooling technique to be used for blades (this technique has been known for more than 20 years, but only for less advanced materials and applications).

Turbine Discs

Besides blades and vanes, the introduction of powder metallurgy disc materials has required a combination of alloy design and process development technologies. Alloy developments for conventionally cast-wrought nickel-base superalloy discs are restricted by the excessive chemical segregation and forging difficulties associated with the levels of alloying additions needed for significantly improved tensile, creep and low cycle fatigue strength. Powder processing has overcome these problems and has led to the development of Astroloy, René 95 and IN 100 having proof strengths some 50% higher than earlier superalloys.

Intermetallic Compounds (IMCs)

Intermetallic compounds being investigated, some of which have near-metallic properties, include nickel and niobium aluminides (NiAl, Ni_3Al and NbAl), dicobalt niobide (Co_2Nb) and molybdenum disilicide ($MoSi_2$) (Ref 8). The alloy NiAl is receiving considerable attention, but still has brittleness problems. If NiAl becomes commercially successful (which is not assured), it will be limited to a use temperature of about 1200 °C. The alloy Co_2Nb is competitive with superalloys in terms of tensile properties, and recently the compound $MoSi_2$ has been alloyed with SiC, yielding interesting results.

Ceramics

The evaluation of ceramics for use in gas turbines started 20 years ago. Extensive research and an expenditure of hundreds of millions of dollars have demonstrated that the high temperature structural (load bearing) ceramics cannot be incorporated into aircraft or industrial gas turbines. Figure 4 illustrates how ceramics and ceramic composites fall short in toughness compared with superalloys. For this section, many data are used from an overview about nonmetallics written by Sims (Ref 8). He uses in this article the superalloy toughness, 16 to 22 MPa $\cdot$ $m^{1/2}$, as the benchmark acceptable toughness for hot-stage use of ceramics and other non-metallic materials.

Revolutionary Steps

Materials are the key to increasing the performance of aircraft gas turbine engines. Estimates have been made that 50% of the improvement in performance will come from improved materials and processes. Reduced leakage contributing another 25% will also rely heavily on better materials (Ref 9). In the USA, the Integrated High Performance Turbine Engine Technology (IHPTET) initiative was launched in the 1980s with the overall goal of doubling turbine propulsion capability, that is a 20:1 thrust-to-weight ratio, by the year 2000. In the UK there is a program with a similar target. The program includes: (i) increasing turbine inlet temperature to over 2000 °C, (ii) reducing the density of materials used in the hot section from 8 g/cm^3 to 5 g/cm^3, and (iii) eliminating component cooling.

IHPTET and other programs include material capability tests in advanced demonstration engines. GE has reported that meeting the demonstration engine requirements needs revolutionary materials (Ref 10) such as: (i) metal matrix composite (MMC) discs, (ii) ceramic matrix composite (CMC) turbine blades and exhaust parts, (iii) lightweight, high-temperature intermetallics, (iv) 370 °C use-temperature polymer matrix composite (PMC) casings and static structures, and (v) TiAl composite blades, and ceramic bearings and dry lubricants.

Capability and potential market estimates are frequently unrealistic, particularly in the field of advanced ceramics. The application of ceramics for critical hot section components could require very long-term development. Continuation of such research must be reconsidered if material costs become excessively high. The task to develop an oxide ceramic having thermal stability at temperatures to 1650 °C for use as a TBC could be far more realistic than to develop a ceramic-matrix composite for use as a load-bearing material in turbine engines.

New materials will remain the centerpiece to more powerful, lighter and more fuel efficient aero engines. Although many more years of research and testing are needed, the aero engines will see intermetallics, MMCs and CMCs substituting partly for today's nickel alloys.

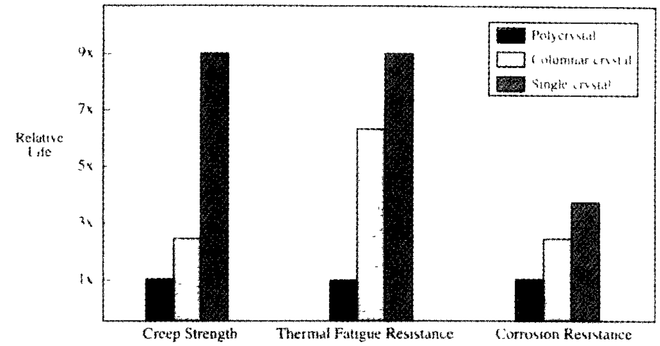

Fig. 3 Comparative properties of polycrystal, columnar and single-crystal superalloys (Ref 4)

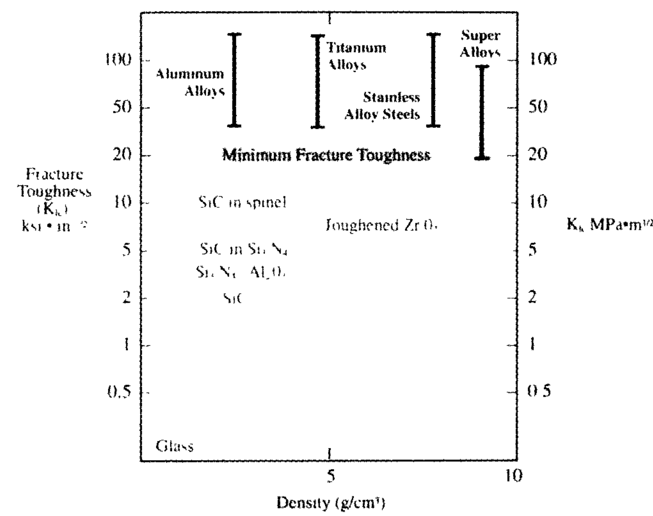

Fig. 4 Fracture toughness between 16 and 22 MPa $\cdot$ $m^{1/2}$ is required in materials for use in gas turbine engines. Ceramics and ceramic-matrix composites currently fall short of this requirement (Ref 8)

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