

High Temperature Materials for Gas Turbines: The Present and Future

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ABSTRACT

Increased operating temperatures and higher efficiency in gas turbines and jet engines can reduce CO₂ emission, thus contributing to the prevention of global warming. To achieve this goal, it is essential to improve the properties of high temperature materials.

Various Ni-base superalloys are used for high-temperature components, e.g., combustors and high-pressure turbine blades and vanes, that determine the power and efficiency of jet engines and industrial gas turbines. Among them, single crystal (SC) superalloys have the highest temperature capabilities. A third-generation SC alloy has been used practically in Jet engines and fourth-generation SC alloys with platinum group metals additions are being developed for the next generation Jet engines. In land-based gas turbines also SC superalloys have been introduced to increase their inlet gas temperatures, and thus thermal efficiencies.

As for new materials, intermetallic alloys, refractory alloys, ceramics, etc., are also being developed as possible alternative materials. Some unique materials have recently been proposed in Japan and being evaluated.

INTRODUCTION

Advancements in materials for high-temperature structural components, such as high-temperature high-pressure turbine materials, have contributed greatly to improving the temperature capabilities and efficiency of jet engines and industrial gas turbines. This paper summarises the history of advancements in Ni-base superalloys for turbine blades and vanes, outlines the achievements made by various gas-turbine projects, and describes how these materials have been applied. A summary of the status of new materials including refractory alloys, ceramics, etc., and future prospects of these materials are also provided in this paper.

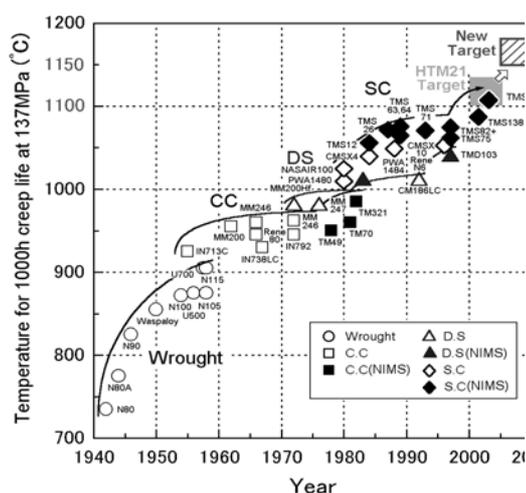


Fig.1 Improvement in temperature capability of Ni-base superalloys, with Japanese project targets for new Ni-base SC superalloys.

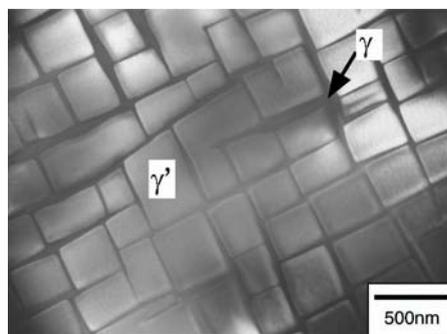


Fig.2 Typical microstructure of the Ni-base SC superalloy with a γ/γ' coherent structure.

NI-BASE SUPERALLOYS

The wrought superalloy was the first superalloy developed and applied to turbines, followed by the introduction of the conventionally cast (CC), directionally solidified (DS) and single-crystal (SC) superalloys. **Fig.1** illustrates the improvement in the temperature capability of the superalloys (Sims, 1987; Harada, 2002), showing that the temperature capability has been improved by 400°C in these 60 years (6.7°C/year). The target temperatures indicated in the figure are the objectives of the High Temperature Materials 21 Project (<http://sakimori.nims.go.jp/>) led by the National Institute for Materials Science, in collaboration with gas-turbine industries. **Fig. 2** illustrates the typical microstructure of the SC alloy. The SC superalloy is continuously being improved. For instance, many researchers are focusing on developing fourth-generation SC alloys containing platinum group metals, such as ruthenium (Ru). **Table 1** shows the composition of typical Ni-base superalloys for turbine blades and vanes.

From Wrought to Cast Alloys

In the 1940s, manufacturers started using wrought alloys, such as Nimonic alloys, for turbine blades and vanes in jet engines. The first step taken to strengthen wrought alloys was to increase the Al and Ti content. The alloys were further strengthened by the enhancement of γ' precipitation and the increase of Mo, W and Nb content. However, difficulties related to forging arose as the alloy strength reached the level of Udimet 700/720. As a solution to this problem, the vacuum-melting technique was introduced in the mid-1950s. Using this technique, Ni-base superalloys containing large amounts of reactive elements contents (e.g., Al, Ti) could be cast to sound CC blades and vanes, which promoted the further strengthening of alloys through increased fraction of γ' precipitation and increased amounts of solid solution strengthening elements. IN738, Rene'80 and MarM247, the typical CC alloys, were developed in the 1960s.

Table 1 Chemical compositions of typical Ni-base superalloys for turbine blades and vanes.

Process	Alloy	Composition (wt%, Ni balance)														Genera tion
		Co	Cr	Mo	W	Al	Ti	Nb	Ta	Hf	Re	C	B	Zr	Others	
CC	IN 738	8.5	16	1.7	2.6	3.4	3.4	-	1.7	-	-	0.17	0.01	0.1	-	-
	IN 792	9	12.4	1.9	3.8	3.1	4.5	-	3.9	-	-	0.12	0.02	0.2	-	-
	Rene'80	9.5	14	4	4	3	5	-	-	-	-	0.17	0.015	0.03	-	-
	MarM247	10	8.5	0.7	10	5.6	1	-	3	-	-	0.16	0.015	0.04	-	-
	TM-321	8.2	8.1	-	12.6	5	0.8	-	4.7	-	-	0.11	0.01	0.05	-	-
DS	GTD111	9.5	14	1.5	3.8	3	4.9	-	2.8	-	-	0.1	0.01	-	-	1 st
	MGA1400	10	14	1.5	4	4	3	-	5	-	-	0.08	?	0.03	-	1 st
	CM247LC	9	8	0.5	10	5.6	0.7	-	3.2	1.4	-	0.07	0.015	0.01	-	1 st
	TMD-5	9.5	5.8	1.9	13.7	4.6	0.9	-	3.3	1.4	-	0.07	0.015	0.015	-	1 st
	PWA1426	12	6.5	1.7	6.5	6	-	-	4	1.5	3	0.1	0.015	0.03	-	2 nd
	CM186LC	9	6	0.5	8.4	5.7	0.7	-	3.4	-	3	0.07	0.015	0.005	-	2 nd
	TMD-103	12	3	2	6	6	-	-	6	0.1	5	0.07	0.015	-	-	3 rd
	TMD-107	6	3	3	6	6	-	-	6	0.1	5	0.07	0.015	-	2Ru	4 th
SC	PWA1480	5	10	-	4	5	1.5	-	12	-	-	-	-	-	-	1 st
	Rene'N4	8	9	2	6	3.7	4.2	0.5	4	-	-	-	-	-	-	1 st
	CMSX-2	4.6	8	0.6	8	5.6	1	-	9	-	-	-	-	-	-	1 st
	TMS-6	-	9.2	-	8.7	5.3	-	-	10.4	-	-	-	-	-	-	1 st
	MC2	5	8	2	8	5	1.5	-	6	-	-	-	-	-	-	1 st
	MDSC-7M	4.5	10	0.7	6	5.4	2	-	5.4	-	0.1	-	-	-	-	1 st
	TMS-26	8.2	5.6	1.9	10.9	5.1	-	-	7.7	-	-	-	-	-	-	2 nd
	PWA1484	10	5	2	6	5.6	-	-	9	-	3	-	-	-	-	2 nd
	Rene'N5	8	7	2	5	6.2	-	-	7	0.2	3	-	-	-	-	2 nd
	CMSX-4	9	6.5	0.6	6	5.6	1	-	6.5	0.1	3	-	-	-	-	2 nd
	TMS-82+	7.8	4.9	1.9	8.7	5.3	0.5	-	6	0.1	2.4	-	-	-	-	2 nd
	YH 61	1	7.1	0.8	8.8	5.1	-	0.8	8.9	0.25	1.4	0.07	0.02	-	-	2 nd
	Rene'N6	12.5	4.2	1.4	6	5.75	-	-	7.2	0.15	5.4	0.05	0.004	-	0.01Y	3 rd
	CMSX-10	3	2	0.4	5	5.7	0.2	0.1	8	0.03	6	-	-	-	-	3 rd
	TMS-75	12	3	2	6	6	-	-	6	0.1	5	-	-	-	-	3 rd
	MC 653	-	4	1	6	5.3	1	-	6.2	0.1	5	-	-	-	3Ru, 0.1Si	4 th
TMS-138	5.8	2.8	2.9	6.1	5.8	-	-	5.6	0.05	5.1	-	-	-	1.9Ru	4 th	
TMS-162	5.8	2.9	3.9	5.8	5.8	-	-	5.6	0.09	4.9	-	-	-	6.0Ru	4/5 th	
ODS	MA6000	2	15	2	4	4.5	2.5	-	2	-	-	0.05	0.01	0.15	1.1Y2O3	-
	TMO-20	8.7	4.3	1.5	11.6	5.5	1.1	-	6	-	-	0.05	0.01	0.05	1.1Y2O3	-

Application of the Directional Solidification Process

The directional solidification process, which became popular in the 1970s, greatly improved the creep strength, ductility and fatigue properties of the longitudinal direction of the turbine blades. The application of this process has contributed significantly to the enhancement of the thrust and reliability of jet engines. One of the first directionally solidified (DS) alloys developed during this period was MarM200Hf. The Hf addition contributes to preventing intergranular cracking during the directional solidification. A similar improvement was made to many other typical CC alloys so that they could be directionally solidified to blades and vanes. Some such alloys widely used today are Rene'80DS and GTD111DS, which are characterized by their relatively high Cr content for good hot-corrosion resistance, and MarM247DS (or CM247DS), which has good high-temperature strength and oxidation resistance.

In the Advanced Gas Turbines Project, which was part of the 1978-87 Moonlight Project funded by the Ministry of International Trade and Industry of Japan, TMD-5 was developed for application in the first-stage blades of prototype plant and was tested for its strength. TMD-5 was the strongest among the first-generation alloys, with strength equivalent to that of the present second-generation DS alloys. Mitsubishi Heavy Industries uses their original superalloys MGA1400 and MGA2400 for the blades and vanes of a 1500°C-class large gas turbine that was put to practical use in 1999 (Kawai, 1997). The use of directionally solidified

MGA1400 in the first and second stages of blades provides the improvement in temperature capability of the components by 50°C, compared with IN738LC (CC alloy).

Second-generation DS alloys contain 3wt% Re, which enhances the solid solution strengthening of the γ phase and has a creep strength equivalent to that of first-generation SC alloys. CM186C and Rene'142 are typical DS alloys widely used in jet engines. TMD-103 (Kobayashi, 1999), developed in NIMS is the first third-generation DS alloy, developed by converting a third-generation SC alloy into a DS alloy by adding the grain-boundary strengthening elements, carbon (C) and boron (B). This alloy has a creep strength equivalent to that of the second-generation SC alloy CMSX-4. **Fig.3** illustrates the strength of DS alloys compared to IN738LC (CC). A fourth-generation DS alloy is also being developed.

The production cost of DS alloys is relatively low because DS alloys have higher casting yields than SC alloys. Therefore, DS alloys are likely to be used widely as turbine vanes and relatively large blades, where casting defects are more likely to occur if the SC casting process is used.

Development and Introduction of SC Alloys

In 1980, SC alloys including PWA1480, Rene'N4, etc., which do not contain grain-boundary strengthening elements such as C, B and Zr were developed. The removal of grain-boundary strengthening elements can significantly raise the incipient melting point and enables solution treatment at temperatures as high as 1300°C or even higher. Thus, these SC alloys with about 70vol% γ' phase can be perfectly solutioned and then ideally precipitated by aging. As shown in **Fig.4**, when SC alloys are used at high temperatures, the raft structure, which is the continuous connection of precipitates, is formed. This raft structure limits the dislocation motion and contributes greatly to increasing the creep strength of the alloy at temperatures exceeding 1000°C.

In 1984, ReneN5 and CMSX-4, typical second-generation alloys that contain 3wt% Re, were developed. In Japan, within Advanced Alloys with Controlled Crystalline Structures Project 1981-88 (Yamazaki, 1991), funded by the Ministry of International Trade and Industry, new superalloys were developed by optimising the composition and structure of SC alloys. These alloys, which do not contain Re and named TMS-12 and TMS-26, were among the best SC superalloys ever developed. Furthermore, extensive research was conducted during the project to develop alloy design

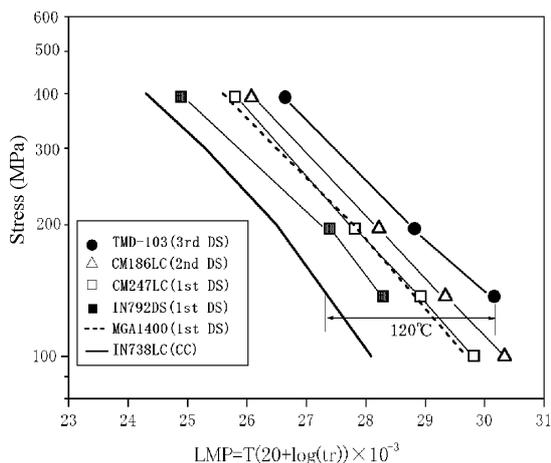


Fig.3 Creep strengths of DS alloys compared with IN738LC(CC).

techniques for SC superalloys.

In the 1990s, much progress was made in the research and development of third-generation SC alloys. Newly developed alloys called Rene'N6, CMSX-10 and TMS-75 were released. Rolls Royce applied CMSX-10 and its improved version, CMSX-10+, under the names of RR3000 and RR3010, respectively, to the uncooled intermediate-pressure turbine blades of their state-of-the-art commercial jet engines, e.g., Trent 800. TMS-75, which was developed in Japan, has relatively good microstructural stability and can be heat-treated easily. Toshiba Corporation has successfully bench-tested TMS-75 in a 1300°C-class 15MW gas turbine.

Currently, the development of fourth-generation alloys containing precious metal elements is underway. General Electric (GE) has achieved improved microstructural stability in SC alloys, which will enhance creep strength during

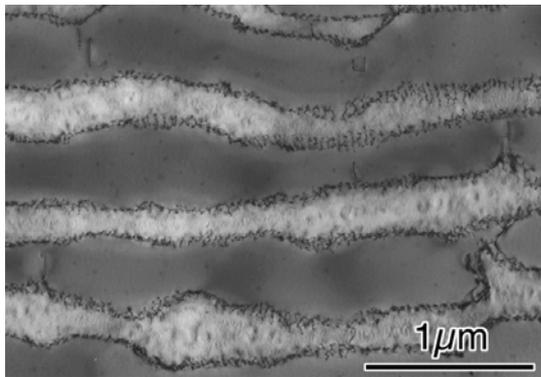


Fig. 4 Typical raft structure of Ni-base SC superalloy after creep under a higher temperature and lower stress condition.

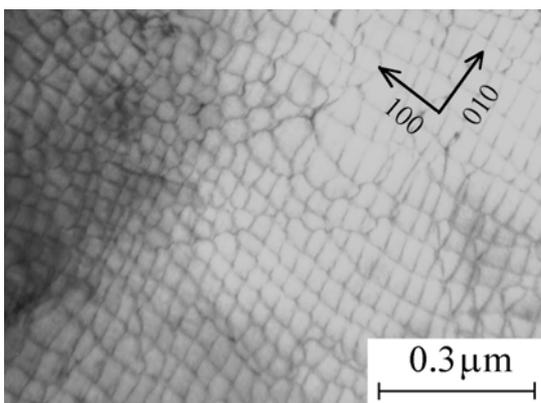


Fig. 5 Stable dislocation network on the interface of the rafted γ and γ' phases in a fourth-generation SC superalloy TMS-138.

long-term exposure at high temperatures; however, details regarding their progress have not been released. In Japan, the High Temperature Materials 21 Project successfully developed fourth-generation SC alloys. One such alloy, TMS-138, was developed by adding a mixture of a strengthening element and Ru or Iridium (Ir) to a SC alloy. The improved strength of these fourth-generation alloys is achieved by an elaborate, stable dislocation network (Fig.5) on the interface of the rafted γ and γ' phases, working as a barrier that prevents dislocation motion through the interface (Zhang, et al., 2002) A supersonic jet engine program conducted by Engineering Research Association for Supersonic Transport Propulsion System (ESPR) funded by the Ministry of Economics, Trade and Industry of Japan, is conducting application research into fourth-generation alloys as the material for turbine blades.

Alloys beyond TMS-138 are being developed. TMS-162 (Koizumi, et al., 2003) is one of such SC alloys and its temperature capability is 1102°C, which is higher than that of TMS-138 by about 20°C.

Since the development of first-generation SC alloys, the temperature capability of SC alloys has been improved by about 100°C.

Application of Single-Crystal Alloys to Gas Turbines for Power Generation

Although SC alloys are widely used in jet engines, their application to land-based gas turbines, e.g., combined-cycle power plants, has been limited due to difficulties involved in the casting process for large blades and vanes. Nevertheless, SC alloys are now put into practical use in Siemens and Alstom/ABB in their newest turbine models.

In Europe, an extensive material property database for CMSX-4 was developed through a project called COST-501, which was led collaboratively by EU nations. In 1998, the COST-522 project was launched with an aim to develop a 1450°C-class power-generation turbine system with 60% thermal efficiency (LHV) (Allen, et al, 1998). In the U.S., the Advanced Turbine System (ATS) Project, funded by the Department of Energy, was launched and the application of SC alloys was promoted. As part of this project, GE applied their second-generation SC alloy called Rene'N5 in the first-stage blades of a 1450°C-class gas turbine.

In Japan, TMS-82+ (Hino, et al., 1999) was developed through the High Temperature Materials 21 Project. This alloy contains a relatively low amount of Re (2.4wt%), and

its strength in a high-temperature and low-stress region exceeds that of third-generation SC alloys. A verification test of TMS-82+ as well as TMS-75 was conducted using a 1300°C-class 15MW turbine. An SC alloys called YH61 (Tamaki, et al., 1999) was developed at Hitachi Corporation and being evaluated. This alloy contains only 1.4wt% Re and has excellent tolerance to low-angle boundaries, good castability and good high-temperature strength.

The 1450-1500°C-class combined cycle power generation system can contribute significantly to reducing CO2 emission from fuel consumption by substituting coal firing steam power plants. In Japan an ultra-efficient (60%HHV) combined-cycle power generation system with higher operating temperature as high as 1700°C is planned. The project will be launched in FY.2004. In this project, new SC superalloys with higher temperature capabilities are to be put into practical use (Fig.6). For this, however, casting technologies for third or fourth-generation SC alloys into larger blades are essential. Also, an excellent thermo-mechanical fatigue property to survive a very large thermal gradient within cooling blade and vane materials is a key.

Oxide Dispersion-Strengthened Superalloys

ODS alloys have excellent creep strengths at temperatures exceeding 1000°C because they are dispersion-hardened by a stable oxide such as Y₂O₃. The MA series (MA6000, etc.)

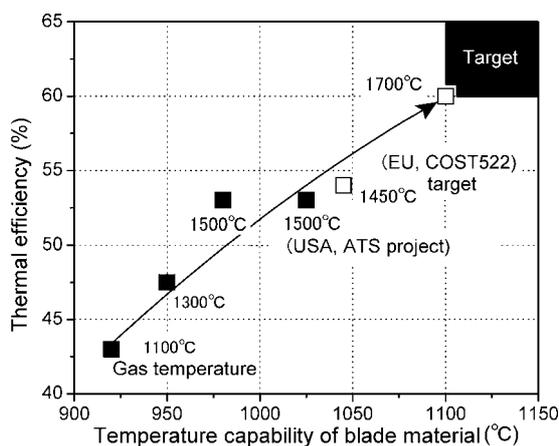


Fig. 6 Advanced SC superalloys with latest cooling/coating systems are to be put into practical use to achieve the ultra-high thermal efficiency.

and PM series (PM3000, etc.) are the ODS alloys currently on the market. In Japan, ODS alloys called TMO-2 and TMO-20 were developed through the Advanced Alloys with Controlled Crystalline Structures Development Project (Kawasaki, et al., 1990). The creep strength of alloy TMO-20 exceeds that of SC superalloys in the whole temperature and stress condition; these properties were achieved by strengthening the base alloy using the alloy design method. Fig.7 compares the creep properties of ODS superalloys with those of SC superalloys.

ODS superalloys that are ductile enough to be forged or rolled into sheets, such as MA754, have good oxide resistance and are suitable high-temperature materials for combustors. However, the above-mentioned TMO-2 and TMO-20 have relatively low ductility (1-3%) and also they are not suitable for manufacturing cooling blades; therefore, their application to turbine blades has not materialised yet. Nevertheless, they are much more ductile than ceramics and intermetallic alloys and can contribute greatly to improving gas temperatures if applied to small, uncooled gas turbine blades and vanes. In order for TMO-2 and TMO-20 to be applied in gas turbines and jet engines, the production cost should be reduced and steps should be taken to ensure the stabilisation and homogenization of material quality across different rods and within the billet.

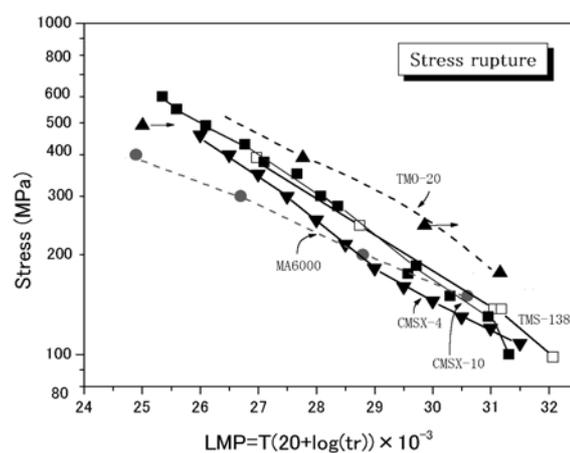


Fig. 7 Creep properties of ODS superalloys compared with several SC superalloys.

EXPECTATIONS FOR NEW MATERIALS

Intermetallic Alloys

Intermetallic alloys generally have poor room-temperature ductility. However, titanium-aluminide (TiAl) base alloys exhibit a certain level of room-temperature ductility and are characterised by their light weight and high specific strength. Currently, the TiAl alloy is the most possible candidate material for low-pressure turbine blades in jet engines. GE has carried out an extensive research on TiAl alloy for the last-stage blade of a low-pressure turbine. The ground test using an actual jet engine was reported to be successful.

In Japan, TiAl base alloys are being investigated in the ESPR Program for a practical use. The Japan Society for the Promotion of Science-related Institutes and Universities (JSPS) initiated a project called the Application of Advanced High-temperature Material (Heat-resistant Intermetallic Alloy) 1996-2000 and conducted extensive research on the use of the directional solidification method to control the crystal orientation and lamellar structure of TiAl base alloys (Yamaguchi, 2000). This project successfully achieved high creep strength in the TiAl alloy without compromising room-temperature tensile ductility. Cost reduction and casting technology to the components seems to be a key for practical applications.

Automobile manufacturers in Japan are already using CC TiAl alloys in turbo-charger rotors (Noda, et al., 2001). Rotor blades made of ceramics tend to be thick due to their limited toughness. On the other hand, the TiAl alloy can be cast as thin blades, making it possible to increase the number of rotor blades and thus enhance turbine efficiency.

Refractory Alloys

Refractory alloys with high melting points are candidate materials for uncooled turbine blades. Among the best-known high melting point alloy is niobium (Nb), which melts at 2468°C. Although Nb exhibits good ductility and its specific gravity (8.58) is equivalent to that of superalloys, its application has been difficult due to poor oxidation resistance. However, alloying Nb with silicon (Si) can produce an alloy with a composite structure consisting of Nb solid solution and Nb-silicide (Nb_5Si_3), which has oxidation resistance equivalent to that of a Ni-base superalloy at 1,200 °C (Jackson, et al., 1996). In Japan, a project called the Advanced Processing Technique for Refractory Alloys 1996-2001, funded by the Ministry of Economy, Trade and Industry, conducted the research and development of various

Nb alloys. Fig.8 illustrates the strength of Nb-silicide alloys that have been strengthened by adding Mo and W (Ma, et al., 1999). The goal of this project was achieved in terms of ultra-high temperature strength, although oxidation properties needed further improvement.

Meanwhile, “refractory superalloys” composed of the γ / γ' structure observed in Ni-base superalloys in platinum group metals with high melting points were proposed in NIMS and being extensively investigated in High Temperature Materials 21 Project. For instance, an alloy developed using iridium (2,447 °C melting point) as a base metal (Fig.9) (Yamabe-Mitarai, et al, 1998) exhibited over 100 hours of creep life in a creep test conducted at 1800°C under 137MPa of stress. Furthermore, this alloy has far better oxidation resistance compared with conventional refractory metals and alloys. Researchers are trying to lower the specific gravity (~

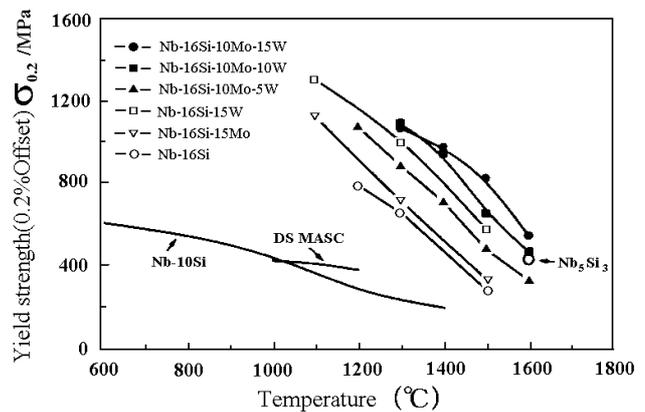


Fig. 8 0.2% yield strength of Nb-silicide base alloys.

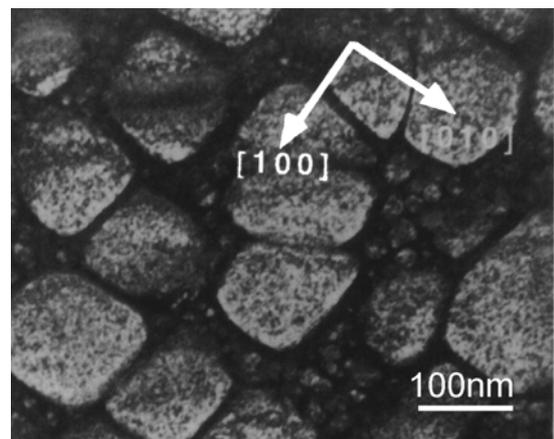


Fig. 9 TEM image of Ir-15at%Nb refractory superalloy.

22) and reduce production cost by using such techniques as mixing it with Ni-base superalloys. Platinum group metals base refractory superalloys is becoming a new field of high temperature materials science and are attracting more researchers all over the world.

Properties of chromium (Cr) alloys have received much attention in recent years. For instance, an Fe-50~60wt% Cr alloy produced by the ultra-high-purity melting process exhibits strength equivalent to Inconel 718 and has excellent ductility and workability at room temperature (Yano, et al, 2002). Also, Cr-W and Cr-Re alloys, which are produced through the ordinary melting process using ordinary materials that have industrially acceptable levels of purity, are reported to have strengths equivalent to or higher than Ni-base SC superalloys at temperatures exceeding 1100°C (Fig.10) (Ro, et al, 2002). Furthermore, the Cr-Re alloy is ductile enough to be machined at room temperature. The resistance against the nitrogen embrittlement during high temperature service, the key for these alloys to be used, is being investigated,.

Ceramics

Over one million turbo-charger rotors for automobiles have been manufactured using silicon nitride (Si₃N₄). Si₃N₄ can be produced by sintering. In the Ceramic Gas Turbine (CGT) Project (1985-2000), Si₃N₄ was applied to the rotor of a small gas turbine, which contributed greatly to increasing the operational temperature and efficiency. Currently, a project called Industrial Co-generation: Hybrid Gas Turbine (1999-2003), funded by the Ministry of International Trade and Industry, is conducting research on increasing the thermal efficiency of gas turbines by using Si₃N₄ material in uncooled turbine vane and other stator parts. An endurance test using an 8MW-class gas turbine operating with inlet gas temperature as high as 1,250 °C is being conducted (Karasawa, 2001).

The High-temperature Material 21 Project is also conducting research to improve the high-temperature strength of Si₃N₄ by crystallising the grain-boundary glass phase (Hirosaki, 2001). Its ultimate goal, that is to achieve 1000 hours of creep rapture life at a temperature of 1,500°C under 137 MPa of stress. This target has recently been achieved with a Si₃N₄ containing lutetium (Lu) and other elements and then is gas-pressure-sintered to crystallise the grain-boundary phase. For practical use, toughness, long-term oxidation resistance and corrosion resistance in high temperature water vapour atmosphere must be

improved.

As for oxide ceramics, a ceramic eutectic called a melt-growth composite (MGC), which was developed in 1997 (Waku, et al., 1997), has gained much attention. MGC maintains consistent strength at temperatures ranging from room temperature to 1,700°C and, like metals, exhibits plastic deformation due to dislocation motion at high

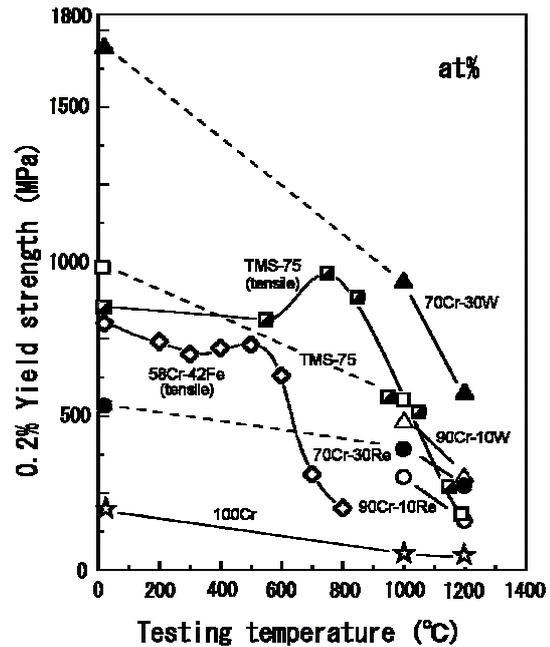


Fig. 10 0.2% yield strengths of Cr base alloys and an SC superalloy TMS-75.

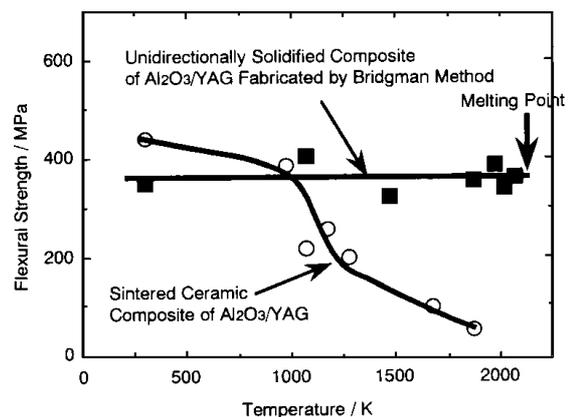


Fig. 11 Strengths of MGC and sintered Al₂O₃/YAG.

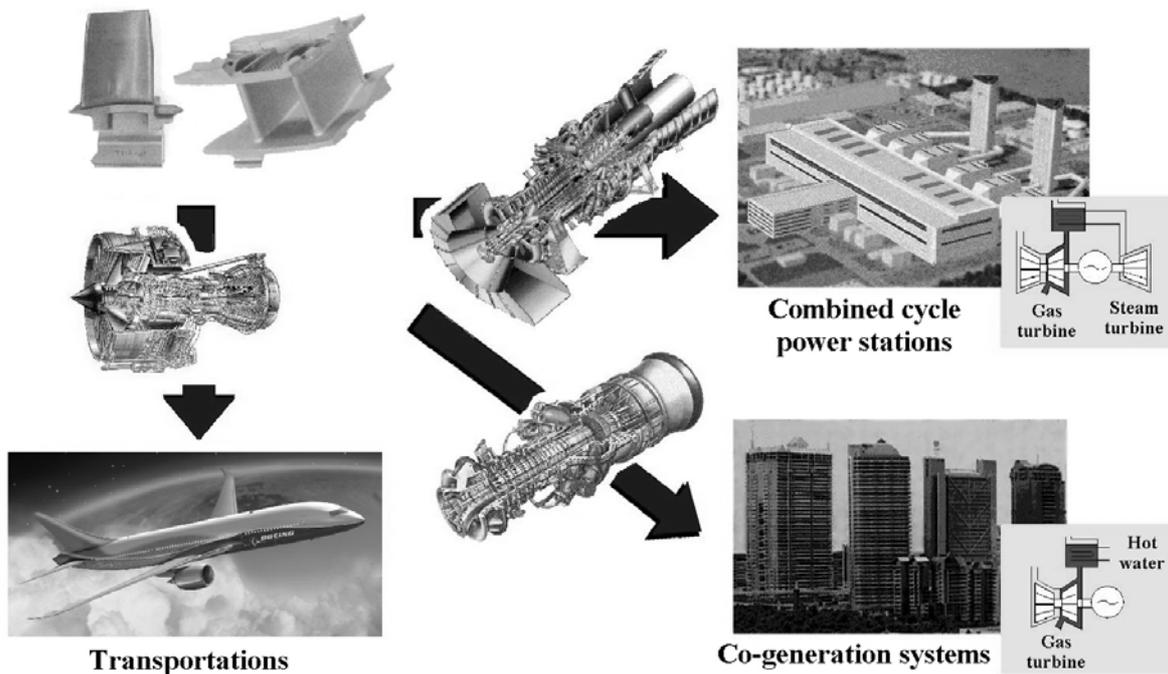


Fig. 12 Effective use of advanced high temperature materials to cut CO₂ emissions from jet engines and land-based gas turbines.

temperatures. It has good oxidation resistance and remain stable during 1000 hours of exposure to air at 1700°C. **Fig.11** compares the reported strength of MGC with that of the sintered ceramic. A project called the MGC Gas-turbine System (2001-2005), funded by the Ministry of International Trade and Industry, is conducting research into the application of MGC, including the production of a prototype uncooled vane for a 1700°C-class gas turbine.

The practical application of ceramic materials depends on whether the room-temperature toughness and thermal shock resistance can be improved.

Composite Materials

Ceramic matrix composites (CMC) have significantly greater fracture resistance compared to the ceramics. Known as lightweight, ultra-high-temperature materials, they are excellent candidates for combustor liners, high-pressure turbine vanes and shrouds. CMCs developed in Japan contain high-quality SiC fibres. Although Japan’s technology in CMC development is very advanced, CMCs are still too costly for practical application. Continuous research should be conducted to enhance environmental resistance properties of the coatings and to develop a technique for controlling the

properties of the fibre-matrix interface.

A carbon-carbon (C/C) composite is a lightweight, high-temperature material which increases its strength in extremely high temperatures up to 2000°C. In order for the use of C/C composites to become practical, the oxidation resistance is expected to be improved through the development of a reliable coating technique.

CONCLUSIONS

The higher efficiency in jet engines and gas turbines can reduce CO₂ emission (**Fig.12**), thus contributing significantly to the prevention of global warming. To achieve this goal, it is essential to improve the properties of high temperature materials so that a higher inlet gas temperature is reached. It is fair to say that Ni-base superalloys will be playing a major role in near future although new materials are desired to be materialised.

Although not much is mentioned in this paper, material design program for Ni-base superalloys, which can be used to predict the microstructure and strength of Ni-base superalloys at high temperatures, was developed in NIMS and practically used in alloy developments. In recent years, a virtual turbine

system (Yoshida, et al., 2001; Saeki, et al., 2002) which links the material design to turbine design and can be used to evaluate materials and predict operating efficiency was developed. The application of these advanced material design techniques will also contribute to enhancing gas turbine technology in power engineering.

References

- Sims C.T., et al. (1987), "Superalloys," John Wiley & Sons, 12.
- Harada H. (2000), *Journal of the Gas Turbine Society of Japan* 28, No. 4: 278.
- Kawai H., Okada I., Takahashi K., Sahira K., Mitsuhashi A., *Materia Japan* 36(1997), 643.
- Kobayashi T., Koizumi Y., Harada H., Yamagata T., Tamura A. and Nitta S., "Materials for Power Engineering 1998," *Proceedings of Conference*, ed. by J. Lecomte-Beckers, et al., 1079.
- Yamasaki M. (1991), "A Handbook for Advanced Alloys with Controlled Crystalline Structures", Japan Standards Association.
- Zhang J. S., Murakumo T., Koizumi Y., Kobayashi T., Harada H., and Masaki S., *Metallurgical and Materials Transactions A*, Vol.33A(2002), 3741.
- Koizumi Y., Kobayashi T., Yokokawa T., Harada H., Aoki Y., Arai M., *IGTC2003*, Tokyo (to be included in this same volume).
- Allen D.H., et al., "Materials for Power Engineering 1998," *Proceedings of Conference*, ed. by Lecomte-Beckers J., et al., 1825.
- Hino T., Ishiwata Y., Yoshioka Y., Nagata K., Kobayashi T., Koizumi Y., Harada H. and Yamagata T., "Gas Turbine Congress 1999, Proceedings of International Conference, Kobe, Nov. 14-19, 1999," 169.
- Tamaki H., Yoshinari A., Okayama A. and Nakamura S., "Materials for Power Engineering 1998," ed. by Lecomte-Beckers J., et al., 1099.
- Kawasaki Y., Kusunoki K., Nakazawa S., Yamazaki M., *High Temperature Materials for Power Engineering 1990*, ed. By E.Bachelet, et al., 1443.
- Yamaguchi M., Johnson DR., Lee HN., Inui H., *Intermetallics*, vol.8, No.5-6(2000), 511.
- Noda T., Shibata T., Okabe M. and Iikubo T., "Report of the 123rd Meeting of the JSPS High-temperature Materials Committee", Vol.40, No.3(1999), 235.
- Jackson M. R., Bewlay B. P., Rowe R. G., Skelly D. W. and Lipsitt H. A., *Journal of Metals*, 48(1996), 39.
- Ma C. L., Kasama A., Tan Y., Tanaka H., Tanaka R., Mishima Y. and Haneda S., "Reports of the 123rd Meeting of JSPS High-temperature Materials Committee" 40, No.3(1999), 349.
- Yamabe-Mitarai Y., Ro Y., Maruko T., Harada H., *Metallurgical and Materials Trans. A*, 29A(1998), 537.
- Yano K. and Abiko K., *Materials Transaction of Japan Institute of Metals (JIM)* 41(2000), 122.
- Karasawa H., *Ceramic Data Book 2001(separate volume), Industries and Products* 29, 83.
- Hirosaki N., *Journal of the Gas Turbine Society of Japan* 29, No. 3(2001): 203.
- Waku Y., Nakagawa N., Wakamoto T., Ohtsubo H., Shimizu K., Kohtoku Y., *Nature*, 389, No. 6646(1997), 46.
- Yoshida T., et al., presented at the 2nd International Symposium on High-temperature Materials 2001, and submitted to *Materials Science and Engineering A*.
- Saeki H., Fukuyama Y., Yokokawa T., Odaka T., Harada H., *Materials for Advanced Power Engineering 2002*, ed. by J. Lecomte-Beckers, et al., 1502.