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Trends in the Development of Heat Resisting Materials for High-efficiency Power Generation Gas Turbines

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1 Introduction

In the Kyoto Conference in 1997 (COP3: The 3rd Session of the Conference of the Parties to the United Nations Framework Convention on Climate Change), Japan's goal for reducing greenhouse gas emission was set to 6% below the level of 1990, and it was written into the Protocol with the condition that the goal should be achieved between 2008 and 2012, and Japan ratified this Protocol in 2002. Thus, development of innovative technologies for the reduction of CO_2 emissions is strongly required from the viewpoint of the prevention of global warming.

While it is well known that the emission of CO_2 originating from the energy conversion sector including power stations can be greatly reduced by replacing thermal power plants with nuclear power plants, current situations do not permit the unfettered construction of nuclear power stations due to various accidents that have occurred recently. Under such circumstances, improvement of the efficiency of thermal power generation, which accounts for a great part of total electric power generation, is desired as a practical means to reduce CO_2 emissions.

It is known that the efficiency of heat engines such as gas turbines and jet engines is effectively improved by raising the temperature of the high temperature side of Carnot's cycle[*1], and, in order to raise the temperature, high-performance heat-resisting materials must be used.

The Council for Science and Technology Policy identified "Advanced materials for environmental preservation and energy utilization" as a priority subject in the fields of nanotechnology and materials, and the performance goal was set to the "Creation and practical application of materials required for the total reduction of CO_2 emissions to achieve the COP3 target." As an example of the technical target, "Development of metallic materials with improved high temperature strength and corrosion resistance that realize the reduction of CO_2 emission per unit thermal power generation by 30%" was cited. Specifically, it is required to develop superheat-resistant metals and turbine system technology that enable the increase of the turbine inlet temperature from the current 1,500°C to 1,700°C.

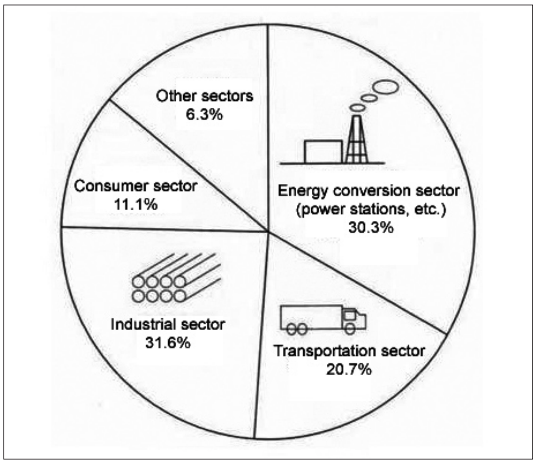
This report reviews the present status of the development of superheat-resistant metals that are indispensable for the realization of ultra-high temperature gas turbines and forecasts future trends in the technology.

2 Development of heat resisting materials as a measure to reduce CO_2 emissions

The necessity for developing measures against global environmental issues including global warming gave a strong impact on the circumstances surrounding heat resisting materials. The breakdown of the total CO_2 emissions in Japan by sectors, which is shown in Figure 1, indicates that the energy conversion sector including power stations accounts for the largest part of about 30%. In respect to power generation, thermal power generation that provides 55% of the total electric power supply is responsible for almost all of the CO_2 deriving from power generation as shown in Figure 2. Under such circumstances, various attempts to improve the operation of thermal power plants that play a central role in the electric power generation are being made. Such attempts include the improvement of generation efficiency by increasing the temperature and pressure, especially by using extra-supercritical pressure, use of natural gas that contains less carbon, and adoption of combined cycle power generation (as described later).

The present average thermal efficiency of thermal power generation using coal and petroleum is about 40% (HHVbasis*2). This means that more than half of the fossil fuels that have been burnt in large quantities are not effectively utilized, emitting a large amount of CO_2 into the atmosphere. Recently, LNG burning power generation that uses liquefied natural gas (LNG) and generates less CO_2 per unit heat quantity has been attracting attention. In particular, LNG combined cycle power generation, in which additional power is generated by driving steam turbines utilizing the steam produced by the waste heat from the gas turbine power generation, provides high thermal efficiency and emits the least amount of CO_2 among the various types of thermal power generation plants. As shown in Figure 3, about 47% of CO_2 per unit electricity generated (kWh) can be reduced by replacing coal-fired power plants with LNG combined cycle power generation plants. Since it is impossible to supply a large quantity of the required energy only with natural energy such as sunlight and wind power, LNG burning combined cycle power generation is now considered to be the last-resort measure to reduce CO_2 emissions in the power generation sector.

Figure 1 : Breakdown of the total CO_2 emissions in Japan[1]



The amount of CO_2 generated by a coal-fired power plant of the 1.2 million kW class accounts for 0.7% of the total emissions in Japan. If this plant is replaced with an ultra-high-efficiency LNG combined cycle power generation plant (gas temperature at the inlet of the turbine is 1,700°C and the thermal efficiency is 60%), the ratio of generated CO_2 is expected to be reduced to as low as 0.3%. The number of domestic major coal-fired power plants (with a capacity of 900,000 kW or more) is 12 and the total output is 17,135,000 kW [5] (as of the end of March 2001). This accounts for about 10% of the total CO_2 emissions in Japan. It should be noted that the introduction of ultra-high-efficiency power plants contributes greatly to the reduction of CO_2 emissions.

Generators of 1,100°C class (gas temperature at the turbine outlet) using the combined cycle were commercialized first. Since the latter half of the 1990s, ACC (Advanced Combined

Figure 2 : Share in electric power supply (left)[2] and CO_2 emissions by power generation methods (right)[3] in Japan

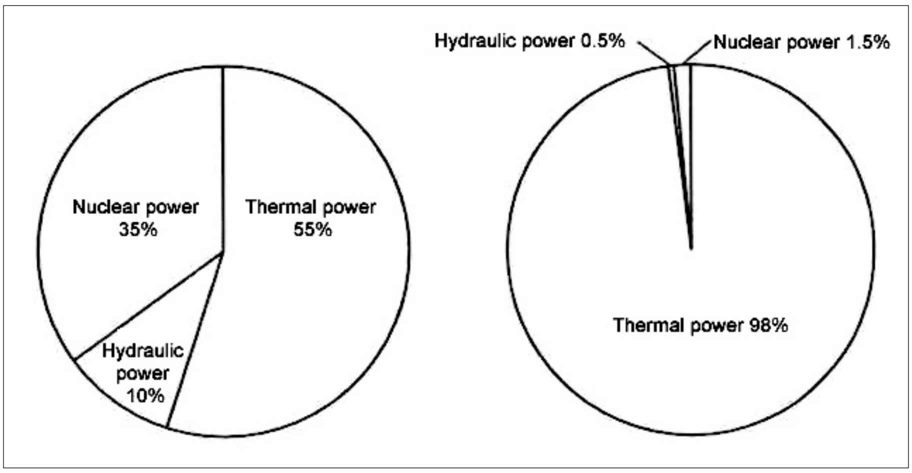
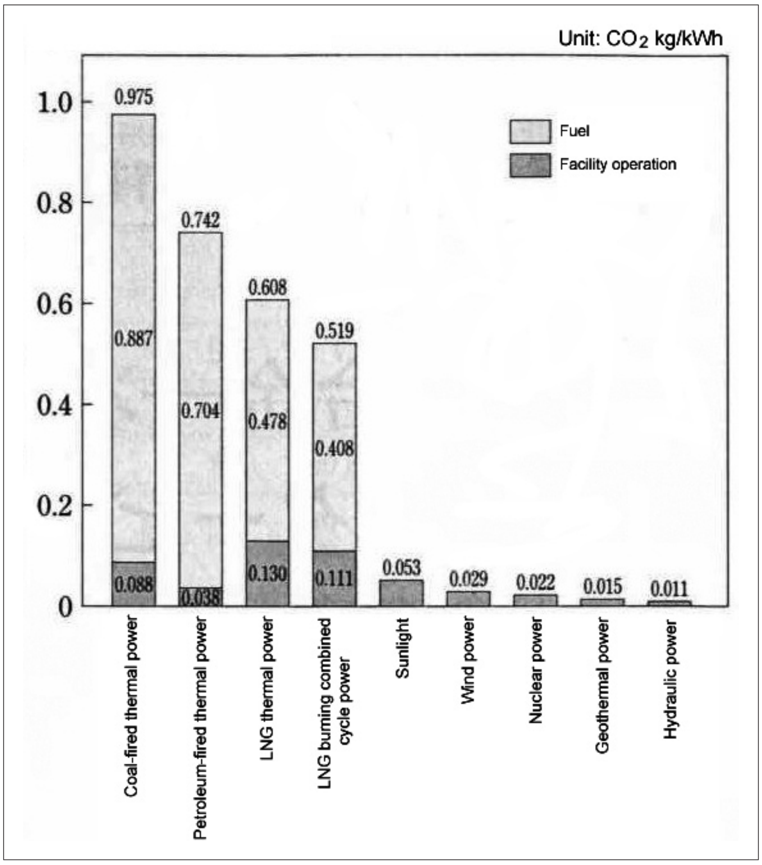


Figure 3 : Comparison of specific CO_2 emission by power sources in Japan[1]



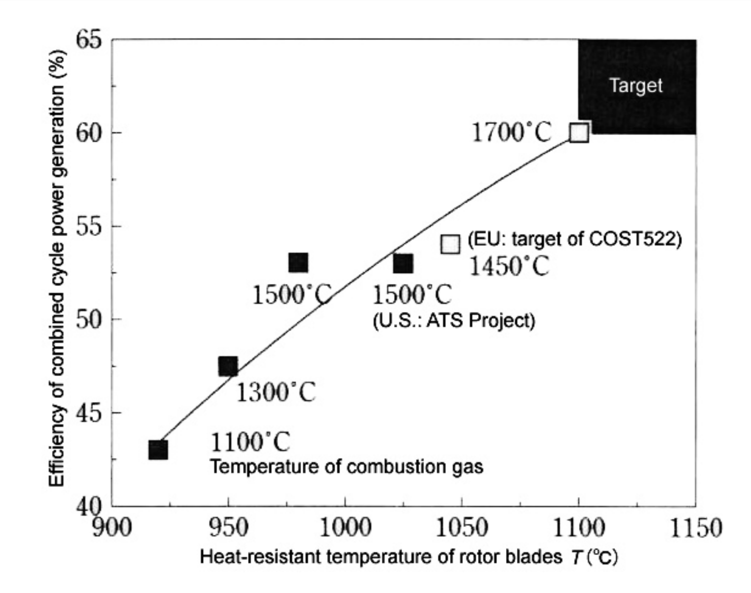
Cycle) generators of 1,300°C class with high thermal efficiency, environmental friendliness, and mobility have become the mainstream of LNG burning power generators. Furthermore, combined cycle power generators of 1,450°C to 1,500°C class, which provide a thermal efficiency of 52% to 54% (HHV basis), have entered the commercialization stage[6, 7].

In the course of the development of these most-advanced gas turbine generators, the heat-resistant temperatures of heat resisting metals including nickel-base superalloys have been improved by utilizing advanced techniques such as unidirectional solidification and single crystal solidification, which means that the development of materials has played an important role. Furthermore, together with the development of heat resisting metals, the cooling technology for turbine blades and ceramic coating material for the heat shielding of the outer surface have been developed.

Figure 4 shows the relationship between the heat-resistant temperature of heat resisting materials and the thermal efficiency of combined cycle generators for commercialized alloys and the target values of projects being carried out by various countries[4]. While the heat efficiency of popular LNG combined cycle generators with inlet gas temperatures between 1,100°C and 1,300°C is in the range between about 43% and 49%, that of 50% or higher has been achieved for generators of the 1,500°C class. It is estimated that a heat efficiency of as high as 60% can be attained when the turbine inlet gas temperature is raised up to 1,700°C. To realize the ultra-high-efficiency gas turbines as a practical solution for the reduction of CO_2 emissions, it is strongly required to develop new superheat-resistant materials for turbine rotor blades and stator vanes.

Referring to Figure 4, in the ATS project of the United States sponsored by DOE, which is a project aiming to develop an advanced turbine system (ATS), a gas turbine of the 1,500°C class has been already developed and commercialized with GE as the main developer. In Europe, the COST522 Project, which started in 1998, is progressing with a target to develop a turbine of the 1,450°C class. In Japan, it is being planned to develop a technology to realize 1,700°C for the inlet gas temperature in order to develop

Figure 4 : Relationship between the efficiency of combined cycle power generation and the heat-resistant temperature of materials used for air-cooled turbine rotor blades[4]



The value indicated as "Target" in the upper right corner of the chart is the target of development for the project being planned by the Ministry of Education, Culture, Sports, Science and Technology, the Ministry of Economy, Trade and Industry, and the National Institute for Material Science, etc.

high-efficiency gas turbines for the electric industry.

The development of heat resisting materials in the United States and Europe is being promoted aiming at the development of jet engines, which is a strategic technology[8, 9], through the cooperation among industry, academia, and government. Contrastingly in Japan, the background is quite different since heat resisting materials are being developed mainly for the development of gas turbines for nonmilitary applications.

In the 21st century, where energy and environmental problems are becoming still more serious, we believe that the strategic importance of heat resisting materials will increase not only from the viewpoint of aeronautical technology but also from the viewpoint of effective utilization of energy.

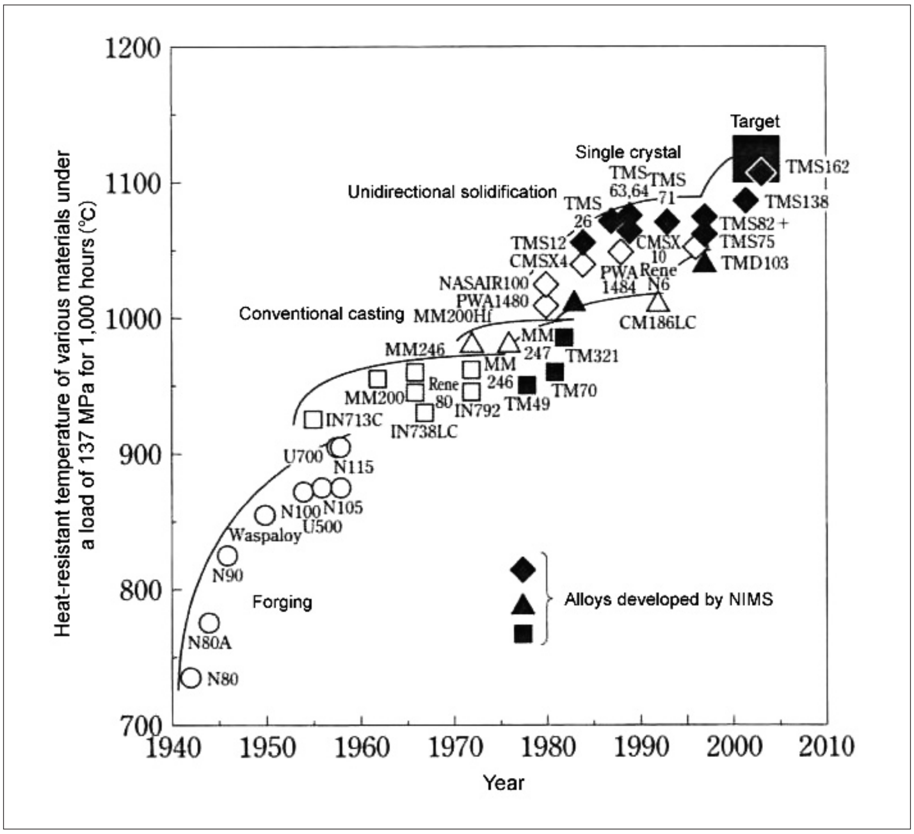
3 History of the development of nickel-base superalloys

The basic properties required for heat resisting materials are strength at elevated temperatures, oxidation resistance, and corrosion resistance. While there are nickel-base, iron-base, cobalt-base, and other alloys for superheat-resistant alloys (superalloys), nickel-base superalloys are being used mainly for the high temperature parts, particularly for combustors and high-pressure turbines that play an important role in improving the output and efficiency of gas turbines for industrial applications and jet engines. Figure 5 illustrates the history of the increase in heat-resistant temperature of nickel-base superalloys[10]. The ordinate axis indicates heat-resistant temperature expressed as the temperature at which creep rupture*3 occurs after 1,000 hours when a stress of 137 MPa is applied. In the gas turbine, there is a temperature difference of several hundred degrees centigrade between the high temperature gas and the heat resisting material, and if the heat-resistant temperature of the heat resisting material is increased, gas temperature of the turbine inlet can be raised correspondingly.

In the "New Millennium Heat Resisting Material Project," which started in fiscal year 1999, an aim is to realize an ultra-high-efficiency gas turbine of the 1,700°C class by increasing the heat-resistant temperature of the material by 100°C, thus allowing the gas temperature to be raised by 200°C.

Nickel-base superalloy products have come through a process of development beginning with forged alloys through ordinary castings and

Figure 5 : History of improvement in the heat-resistant temperature of nickel-base superalloys[10]

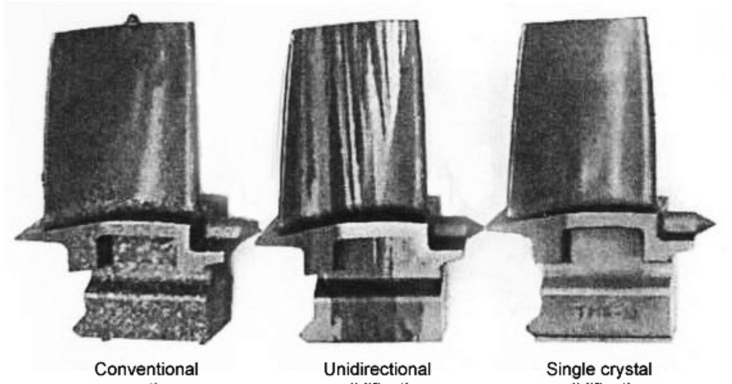


Heat-resistant temperatures are those at which creep rupture life is 1,000 hours under a load of 137 MPa.
○ :Forged (wrought) alloys, □ : Conventional castings (CC) alloys, △ :Directionally solidified (DS) alloys, ◇ : Single crystal (SC) alloys. Black marks indicate alloys that were developed by the National Institute for Material Science (former National Research Institute for Materials).
"Target" shown in the chart indicates the target of development for the New Millennium Heat Resisting Materials Project.

directionally solidified alloys, and finally to single crystal alloys. In the 1940s, forged (wrought) alloys such as N80 were developed and applied to rotor and stator blades of turbines. However, as the materials were strengthened by precipitation strengthening and other techniques, it became increasingly difficult to fabricate by forging. In the middle of 1950s, the vacuum melting technology was developed and precision casting of conventionally cast (CC) products of alloys containing large amounts of active elements such as aluminum and titanium was made possible using cores*4. This further promoted the development of precipitation strengthening and solid-solution strengthening. However, the problem was that the alloys obtained by such process had a structure containing a large number of crystal grains and the grain boundaries caused the start of fractures. In the case of turbine rotor blades, in particular, cracks were caused along the grain boundaries after a long period of use due to the centrifugal force resulting from the high-speed rotation of blades at high temperature.

To solve this problem, attempts were made to eliminate grain boundaries perpendicular to the longitudinal direction, in which fatigue and creep rupture were apt to occur, from turbine rotor blades using directionally solidified alloys and single crystal alloys that were prepared by controlling the crystal structures. Around 1970, application of the directionally solidified (DS) process was started, and the creep strength, ductility, and fatigue properties in the longitudinal direction of turbine rotor blades were significantly improved by arranging the direction of grain boundaries approximately parallel to the centrifugal force generated in the longitudinal direction. Furthermore, single crystal (SC) alloys were developed around 1980, in which all the grain boundaries were eliminated so that high temperature strength

Figure 6 : Turbine rotor blades fabricated by conventional casting, unidirectional solidification, and single crystal solidification[12]



was largely improved. Figure 6 illustrates turbine rotor blades produced by conventional casting, unidirectional solidification, and single crystal solidification processes. The preferred orientation of crystal growth obtained by the unidirectional solidification provides high creep strength and thermal fatigue resistance[11].

In addition, oxide-dispersion-strengthened (ODS) superalloys that have creep strength higher than that of single crystal superalloys have been developed[11, 12]. These alloys are produced by a series of processes–mechanical alloying → extrusion → unidirectional recrystallization. These alloys have excellent high temperature creep strength particularly at temperatures higher than 1,000°C, because fine particles of oxide such as yttrium oxide (Y_2O_3) that are stable when used at high temperatures for a long time are uniformly dispersed. Alloys of this type that can be forged or rolled into sheets are used for high temperature components such as combustors, but full-fledged application to turbine rotor blades has not been realized because the ductility is insufficient and it is difficult to fabricate air-cooled blades. A subject also to be pursued is to produce stable and uniform material and reduce the cost of manufacturing.

While the heat-resistant temperature of alloys was about 730°C immediately after development in the beginning of 1940s, those of present alloys have been raised to 1,100°C. The improvement of 350°C to 400°C in the heat-resistant temperature took almost 60 years, which is a typical example of the development of structural materials that requires a long period of time for the gradual progress in the improvement of properties.

Table 1 shows compositions of typical nickel-base superalloys for turbine blades[12]. All the alloys have complicated compositions containing approximately 10 component elements. The alloying elements are added to improve various characteristics including strength, corrosion resistance, oxidation resistance, casting characteristics, and heat treating characteristics. The alloys are classified into four groups according to their compositions: alloys of the first generation from the initial stage of development, alloys of the second generation that contain about 3 mass % of rhenium (Re), alloys of the third generation that contain 5 to 6 mass % of rhenium, and the newest alloys of the fourth generation that contain precious metals such as ruthenium (Ru).

It is particularly notable that all the alloys except for TMS developed by the former National Research Institute for Materials have been developed by private companies. PWA, Rene, and CMSX have been developed by U.S. manufacturers, MC by a French manufacturer, and MDSC by a Japanese manufacturer. Particularly in the United States and Europe, since the development of engines for the aerospace industry was prevalent, the governments supported the development of private companies, and, as a result of collaboration between government and industry, development was accelerated[9].

Table 1 : Compositions of typical nickel-base superalloys for turbine blades (mass %, Ni: remaining)[12]

Type	Name of alloy	Alloy composition														Remarks
		Co	Cr	Mo	W	Al	Ti	Nb	Ta	Hf	Re	C	B	Zr	Others	
CC	IN738	8.5	16	1.7	2.6	3.4	3.4	–	1.7	–	–	0.17	0.01	0.1	–	–
	IN792	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	–	–	1st
	CM247LC	9	8	0.5	10	5.6	0.7	–	3.2	1.4	–	0.07	0.015	0.01	–	1st
	TMD-5	9.5	5.8	1.9	13.7	4.6	0.9	–	3.3	1.4	–	0.07	0.015	0.015	–	1st
	PWA1426	12.0	6.5	1.7	6.5	6	–	–	4	1.5	3	0.1	0.015	0.03	–	2nd
	CM186LC	9	6	0.5	8.4	5.7	0.7	–	3.4	–	3	0.07	0.015	0.005	–	2nd
	TMD-103	12	3	2	6	6	–	–	6	0.1	5	0.07	0.015	–	–	3rd
SC	PWA1480	5	10	–	4	5	1.5	–	12	–	–	–	–	–	–	1st
	Rene' N4	8	9	2	6	3.7	4.2	0.5	4	–	–	–	–	–	–	1st
	CMSX-2	4.6	8	0.6	8	5.6	1	–	9	–	–	–	–	–	–	1st
	MC2	5	8	2	8	5	1.5	–	6	–	–	–	–	–	–	1st
	MDSC-7	4.5	10	0.7	6	5.4	2	–	5.4	–	0.1	–	–	–		1st
	TMS-26	8.2	5.6	1.9	10.9	5.1	–	–	7.7	–	–	–	–	–	-	2nd
	PWA1484	10	5	2	6	5.6	–	–	9	–	3	–	–	–	–	2nd
	Rene' N5	8	7	2	5	6.2	–	–	7	0.2	3	–	–	–	–	2nd
	CMSX-4	9	6.5	0.6	6	5.6	1	–	6.5	0.1	3	–	–	–	–	2nd
	TMS-82	7.8	5	3.4	8.7	5.2	0.5	–	4.4	0.1	2.4	–	–	–	–	2nd
	YH61	1	7.1	0.8	8.8	5.1	–	0.8	8.9	0.25	1.4	0.07	0.02	–	–	2nd
	Rene' N6	12.5	4.2	1.4	6	5.75	–	–	7.2	0.15	5.4	0.05	0.004	–	0.01Y	3rd
	CMSX-10	3	2	0.4	5	5.7	0.2	0.1	8	0.03	6	–	–	–	–	3rd
	TMS-75	12	3	2	6	6	–	–	6	0.1	5	–	–	–	–	3rd
ODS	MA6000	2	15	2	4	4.5	2.5	–	2	–	–	0.05	0.01	0.15	1.1Y203	–
	TMO-20	8.7	4.3	1.5	11.6	5.5	1.1	–	6	–	–	0.05	0.01	0.05	1.1Y203	–

In the Type column; CC: conventional casting, DS: directional solidification, SC: single crystal solidification, and ODS: oxide-dispersed-str engthening.
In the Remarks column, 1st, 2nd, and 3rd indicate the generations of alloy development.

4 Development of new materials expected to be commercialized in the future[12]

Attempts are being made to develop new materials far superior to nickel-base superalloys in heat-resistant temperature. So far, the materials that have been developed are not yet reliable enough to substitute nickel-base superalloys, but it is hoped that innovative heat resisting materials that are satisfactory for practical use will be developed in the future.

• Ceramics

Ceramics are expected to become heat resisting materials superior to metals. Particularly, silicon nitride ceramics are already being used for mechanical parts such as those for automobile engines. They are appreciated as reliable materials with corrosion resistance, strength, and toughness in the temperature range of 1,000°C or lower. However, they cannot be used for gas turbines because the strength decreases in the temperature range higher than 1,000°C. Recently, it has been reported that a material whose strength was maintained up to 1,500°C was developed by improving heat resistance through control of the composition of the grain boundary phase, which caused the decrease in strength at elevated temperatures. It is strongly hoped that the reliability of these materials at elevated temperatures will be improved by enhancing toughness and other properties.

• Intermetallic compound alloys

TiAl intermetallic compounds have a specific gravity that is about half the specific gravity of nickel-base alloys, the specific strength and specific creep strength comparable to those of nickel-base alloys, and higher specific rigidity than that of nickel-base alloys. Although intermetallic compounds are generally poor in ductility at ambient temperature, TiAl-base alloys are considerably ductile at ambient temperature having characteristics of high specific strength and lightness; so it seems that they are very close to practical use. Although cost effectiveness still remains a problem, it is intended in the "Research and Development of Environmentally Compatible Propulsion System for Next-generation Supersonic Transport (ESPR)" sponsored by the Ministry of Economy, Trade and Industry to use these intermetallic compounds for the blades of low-pressure turbines and stationary parts. Successful results including the combination of excellent creep strength and tensile ductility at ambient temperature have already been achieved through controlling the crystal orientation by unidirectional solidification as well as the metallographic structure. At present, studies to establish forming technologies that enable the fabrication of complicated shapes and improve strength at elevated temperature[11] are being carried out.

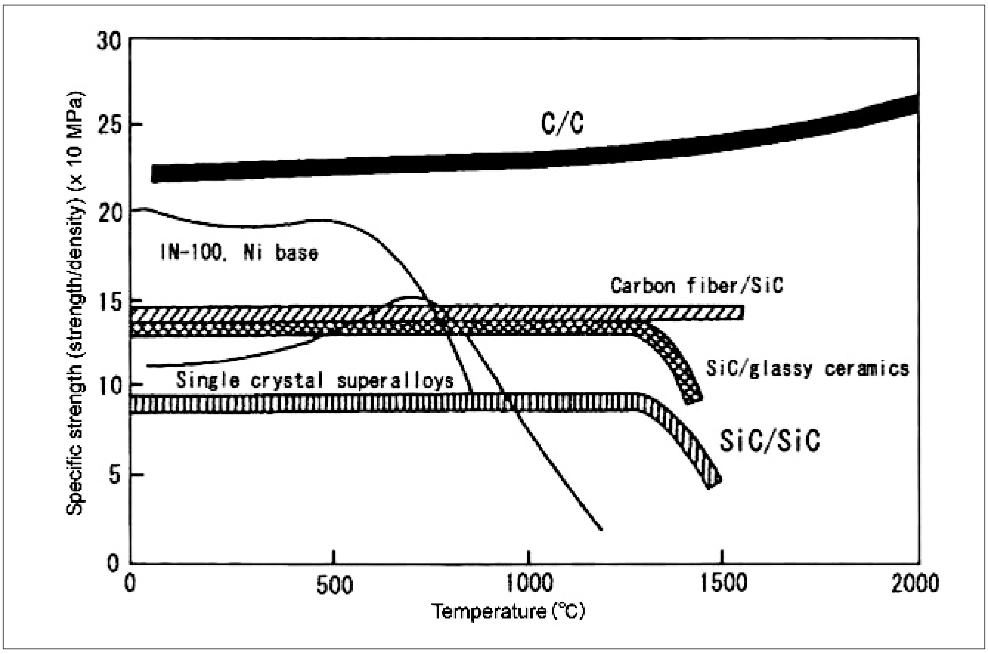
• Refractory metals

Refractory metals are expected to be used for uncooled blades. Among the refractory metals, niobium (Nb) has a specific gravity comparable to that of superalloys and excellent ductility in addition to the high melting point of 2,468°C. It has high temperature strength that enables its use at as high as about 1,500°C. The only problem for practical use is its poor oxidation resistance. However, it has been found that oxidation resistance is improved up to about 1,200°C by adding silicon to niobium, thus providing the complex structure of niobium solid solution and niobium silicide. This oxidation resistance is comparable to that of nickel-base superalloys. Niobium alloys are also being developed in the "Advanced Fabrication Technology for Refractory Metal Parts" project sponsored by the Ministry of Economy, Trade and Industry, and significant improvement in high temperature strength has been reported. However, the combination of oxidation resistance and strength has not yet been achieved.

Refractory superalloys using refractory metals other than niobium alloys have also been developed and have similar structures to those of nickel-base superalloys. Iridium alloys based on iridium, a platinum group metal having a melting point of 2,447°C, have a high melting point and very high elastic modulus at ambient temperature so that they have possibilities for heat resisting materials. In addition, these alloys have an improved oxidation resistance compared with conventional refractory metal alloys. However, they have not reached a practical level because other required characteristics such as specific gravity and cost are not yet satisfactory. Other platinum-family-base superalloys using rhodium and platinum have been developed[13]. Although these alloys have reached the level of practical use, the know-how obtained from the experience of these alloys is being utilized for the effective addition of alloying elements to nickel-base superalloys and the coating materials of nickel-base superalloys.

Conventional chromium alloys have a problem in that they are lacking in ductility, and strength decreases when attempts are made to improve ductility. However, they are now attracting attention once more because it has been reported that excellent ductility and workability at ambient temperature were obtained together with strength comparable to or better than conventional chromium alloys by applying an ultrahigh-purity melting process. It has also been reported that high temperature strength superior to nickel-base single crystal

Figure 7 : High temperature strength of various composite materials[14]



Both IN-100 and Single crystal superalloys are nickel-base superalloys.

superalloys was obtained in the temperature range exceeding 1,100°C by chromium-tungsten alloys or chromium-rhenium alloys prepared by a conventional melting process. Since chromium alloys suffer from embrittlement caused by the intrusion of nitrogen at high temperature, it is hoped that this problem will be solved in the future.

• Composite materials

It is hoped from the viewpoints of heat resistance and weight saving that composite materials such as metal matrix composites (MMC), ceramic matrix composites (CMC), and carbon carbon composites (C/C) will be developed.

Research on metal matrix composites (MMC) is being conducted from the viewpoints of weight saving and improvement in specific gravity, and materials based on aluminum, titanium, and intermetallic compounds have been developed. While research on the fabrication of parts using these materials is being conducted in the “Research and Development of Environmentally Compatible Propulsion System for Next-generation Supersonic Transport (ESPR)” project, it is also necessary for practical use to establish a database for designing as well as to reduce production cost.

Figure 7 shows the relationship between temperature and specific strength for SiC-base composites and carbon-base composites compared with the relationship for nickel-base superalloys. It is seen from the chart that these composite materials, in contrast to nickel-base superalloys, retain strength even in the high temperature range exceeding 1,000°C.

Ceramic matrix composites (CMC) consist of ceramics that have a specific gravity about one-third to a quarter that of nickel-base superalloys as well as a heat-resistant temperature exceeding 1,200°C, and reinforcing fiber such as SiC. They have fracture resistance far greater than that of conventional ceramics and they are expected to be used for combustor liners, stator vanes of high-pressure turbines, shrouds, etc., as ultra-light heat resisting material applicable to ultra-high temperature ranges. Since excellent SiC fiber materials are available in Japan, the technological level of Japan is high in this field. Although reduction of production cost is the most important issue for commercialization, development of process technologies including the structure control of the interface between the fiber and matrix and coating for the improvement of environmental resistance is also required.

Carbon carbon composite (C/C) is considered to be a promising light-weight, heat resisting material because it retains strength up to the ultra-high temperature of 2,000°C, However, oxidation resistance in high temperature gas atmosphere is an obstacle to commercialization, and it is an important issue to increase reliability in practical environments by developing such technologies as coating.

All of these composite materials are still in the stage of development and have not been put to practical use. There remain problems to be solved such as the fabrication of complicated shapes and environmental resistance in high temperature. In addition to the improvement in material characteristics, therefore, it is desired to establish process technologies and improve reliability.

• **Thermal barrier coating (TBC)**

As the operating conditions of gas turbines become severer due to the higher gas temperature, most of the parts made of nickel-base superalloys that are exposed to particularly high temperature such as the turbine blades and combustors are coated with coating materials from the viewpoints of corrosion resistance, oxidation resistance, thermal barrier, etc. Above all, the importance of thermal barrier coating is increasing as a result of increasing gas temperature. Yttria-stabilized zirconia is coated on the alloy surface by spray coating or electron-beam physical vapor deposition (EB-PVD), and at the same time the inside of rotor blades and stator vanes is cooled by forced cooling. By doing so, a large temperature gradient is created across the coating layer so that the rise of the temperature of the metal is suppressed. Materials that have a relatively large thermal expansion coefficient (close to that of metals) and small thermal conductivity are desirable for the oxides to be coated. Materials that do not deteriorate or exfoliate during a long period of use are being explored and developed.

Directionally solidified (DS) nickel-base superalloys, single crystal (SS) materials, thermal barrier coating (TBC) materials, etc., are now being used for the most-advanced turbines and are contributing, together with the development of the cooling technology, to the significant increase in gas temperature and generation efficiency. New materials including ceramics are also being used for some parts such as combustion chambers on a trial basis, but it has not yet been established which of these new materials will be used practically in the future. Under such circumstances, it is necessary to continue comprehensive research and development of new materials on a wide range, and, at the same time, it also seems necessary to conduct research on system design conforming to the characteristics of new materials with a perspective on full-scale application in the future. Therefore, development of material technologies must be carried out in cooperation with system designers taking structure stability and reliability in the long period of service under severe conditions into consideration.

5 Conclusion

In this report, trends in technical development of heat resisting materials have been reviewed from the viewpoint of measures for the reduction of CO_2 emissions. Heat resisting materials are key materials that significantly affect the heat efficiency of advanced heat engines such as gas turbines and jet engines, and their development is a very important cross-sectional subject that covers a wide range of fields including environment, energy, and materials from the viewpoint of saving energy and resources.

Originally, heat resisting materials started as strategic materials used for military applications such as jet engines, they were developed for military purposes in Europe and the United States, whereas the background is completely different in Japan because these materials have been developed for use in the civilian sector. In Japan, the former National Research Institute for Materials (present National Institute for Material Science) led the research and development of heat resisting materials. Globally, however, private companies have played important roles in the research and development of high-efficiency gas turbines and superheat-resistant materials. In Europe and the United States, the governments have helped private companies to develop heat resisting materials in line with the national policy relating to the development of jet engines. In this sense, it may be said that governments played a significant role in the development of heat resisting materials in all the countries of Japan, Europe and the United States.

Today, heat resisting materials have become strategically important from the viewpoint of advanced utilization of energy. In order to dispel environmental problems on a global basis, Japan must enhance international competitiveness in the world market of heat resisting materials and gas turbines through the strengthening of technology. Currently, the heat-resistant temperature of Japanese turbines is at the highest level in the world, and it is expected that Japan will take the leadership in the development and commercialization of next-generation gas turbine systems by developing heat resisting materials that have still higher heat-resistant temperatures.

As a challenge to global environmental conservation, the Japanese government should promote research and development and help with the commercialization and industrialization of the results. However, the past history of the development of superalloys has proved that development of materials takes time. Although nickel-base superalloys are expected to be used for the next-generation gas turbines, it is possible that ceramics and refractory metals that have higher heat-resistant temperatures will be put into practical use thereafter. Therefore, it is necessary to promote the development of these materials in parallel, and, in addition, continuous government aid based on a long-term perspective is required for the lasting development of technologies.

The methodology and time schedule for achieving the target of the CO_2 reduction were proposed in the roadmap for the heat resisting material strategy prepared by the Materials Strategy Committee of The Japan Institute of Metals. In this roadmap, the necessity of developing high-efficiency turbines and superheat-resistant materials was pointed out. In order to put newly developed technologies to practical use, it is necessary to promote the development with close cooperation between the system sector and material sector. This means that industry, academia, and government must further collaborate in order to establish concrete plans for development. In this sense, planning to start from fiscal year 2004, the "Development of elemental technologies for commercialization of high-efficiency gas turbines" project sponsored by the Ministry of Economy, Trade and Industry and the "Development of commercial superheat-resistant materials" project should collaborate, keeping close relationship between the system sector and material sector so that ultra-high-efficiency thermal power generation technology is developed through collaboration among industry, academia, and government.

Today, when the collaboration among industry, academia, and government is advocated, what is expected of the government is to provide an environment that efficiently enables cooperation and appropriate division of roles in research and development through the establishment of a framework for interdisciplinary technical exchanges making use of academic societies and industrial associations as well as coordination of such exchanges. It is also necessary to establish technical bases such as the construction of databases relating to the material characterization technology and elemental technologies for system design.

As the severe economic situation continues, to enhance and maintain international competitiveness of manufacturing industries, which are expected to lead economic revitalization, it is required to continuously promote the development of materials that serve for the minimization of burdens on the environment. Therefore, a subject for investigation is how to provide private companies with incentives including preferential taxation that would activate research and development and practical applications of materials and manufacturing technologies effective for saving energy and resources.

Acknowledgement

This report has been compiled based on the lecture "Strategy for the commercialization of superheat-resistant materials and ripple effects on the energy industry-from jet aircraft to power engineering" given by Mr. Hiroshi Harada, director of the High Temperature Materials Group, National Institute for Material Science, on September 11, 2003, with the added results of investigation made by the Science and Technology Foresight Center. The author would like to sincerely thank Mr. Harada for his advice and provision of material relating to this report.

Notes

*1 A heat engine that makes a gas undergo isothermal expansion, adiabatic expansion, isothermal compression, and adiabatic compression. Its efficiency η is given by $\eta = 1 - T_L/T_H$, where T_L and T_H are absolute temperatures of the low temperature heat source and high temperature heat source, respectively.

*2 Higher heating value basis. This indicates a condition for expressing the energy (heating value) of a fuel. The higher heating value (HHV) includes the heat of condensation (latent heat of vaporization) of the steam deriving from the water contained in the fuel and generated by combustion, whereas the lower heating value (LHV) dose not include the latent heat of vaporization. Therefore, values of generation efficiency expressed on the higher heating value bases are lower than those expressed on the lower heating value basis.

*3 A phenomenon in which the material does not break instantaneously but deforms gradually over a long period of time, finally resulting in rupture when a certain constant stress is applied while the specimen is kept at a high temperature. This is the most important property for structural materials used for equipment such as gas turbines, jet engines, and boilers that is used for a long period at high temperatures.

*4 A mold that is inserted into the cavity of the main mold when a casting with a hollow is made.

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(Original Japanese version: published in January 2004)