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AERO-ENGINE BUSINESS AND MATERIAL TECHNOLOGIES IN JAPAN

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Abstract

Japanese research activities on jet engines began in the 1940s and progressed as far as the test flight of the Ne-20 jet engine. All work was discontinued, however, at the end of World War II. After seven years, production of jet engines was permitted to resume, as the major defense equipment mainly under licenses with European and American manufacturers. Efforts were subsequently continued to develop more advanced technologies, which were then applied to design and manufacture the civil and military engines. Full-scale development of superalloys and other engine materials began in Japan as a part of multiple national programs aimed at developing new gas turbines. A number of original materials and process technologies have been studied. This paper addresses the current and future material technologies in Japan.

Business Overview

It is generally predicted that the number of airline passengers throughout the world will grow at a rate of about 5% per year until 2020. Demand is expected to grow rapidly especially in the Asia-Pacific region. The aero-engine industry in Japan has grown considerably in the last half century. Total production in fiscal 2001 was worth approximately $23 million, about twice the amount sold in fiscal 1985. Japanese production accounts for several percent of the total world market; it is equivalent to about one-ninth of the American production, and equal to the production of Germany or Canada. Despite the lingering affects of the war in Iraq and SARS, the long-term prospects for the aero-engine industry are strong, making it an exception to the general malaise that currently afflicts so many other Japanese industries. The nature of the business has changed drastically in recent years, as well. Although the field of defense retains its historical importance, it accounts for a decreasing share of total aero-engine sales, declining from 75% in the 1980s to about 60% today. In the past several years, it has been predicted that civil engines will eventually outsell those for military use. The other major change has been the expansion of related maintenance and service sectors, and the increased provision of component production services to the major manufacturers in the US and Europe. Generally speaking, maintenance and service industries are increasingly being localized, and production is becoming more specialized throughout the world. In the future, Japanese manufacturers expect to develop their own next-generation engines, one for patrol planes for defense, and one for small regional planes (50-seat class) for the civil market.

Jet Engine Development

Japanese research activities on jet engines began in the 1940s and progressed as far as the test flight of the Ne-20 jet engine on a prototype of the Nakajima Kikka (Orange Blossom) jet fighter.

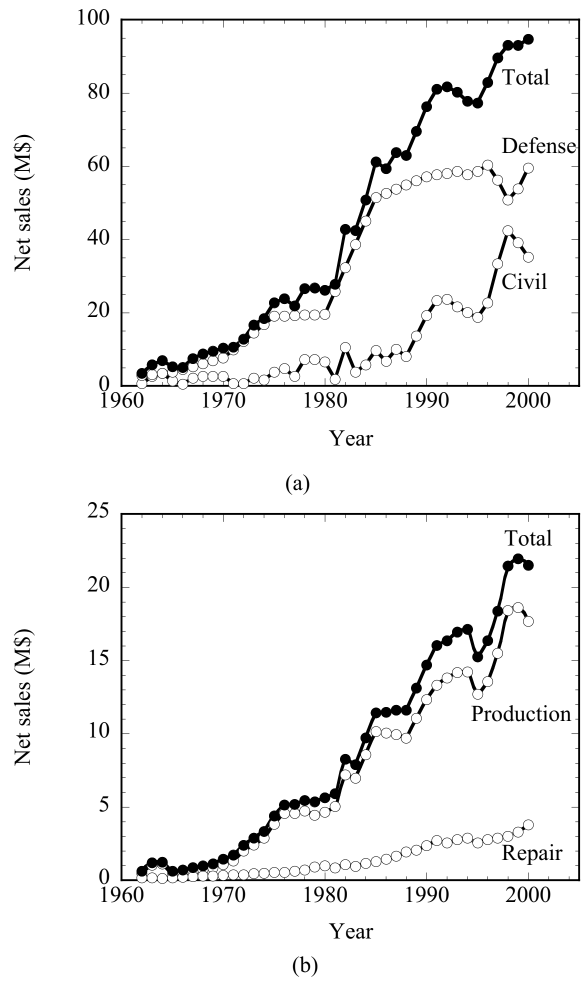


Figure 1. Net sales of Japanese air craft industry (a) defense and civil, (b)aero engine production and repair.[1]

All work was discontinued, however, at the end of World War II. After seven years, production of jet engines was permitted to resume, as the major defense equipment mainly under licenses with European and American manufacturers. Research and development by the Technical Research and Development Institute of the Japan Defense Agency also commenced at that time, leading to the domestic manufacture of turbojet engines for intermediate jet trainers such as the J-3 in the 1960s. Efforts were subsequently continued to develop more advanced technologies, which were

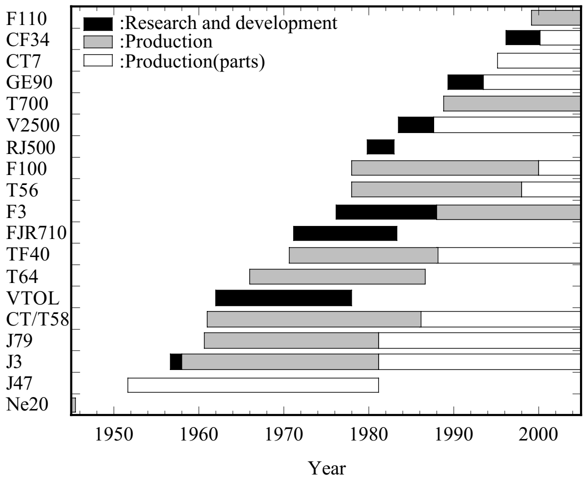


Figure 2. Research, development and production of jet engines in Japan.

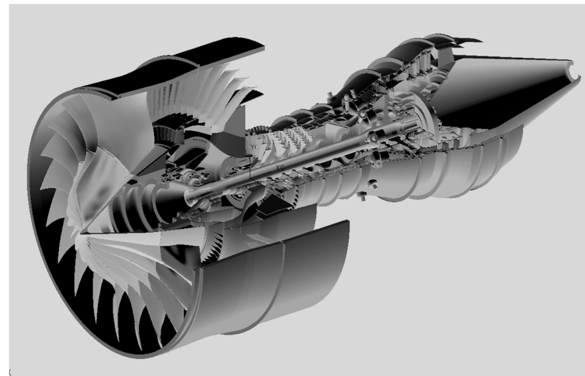


Figure 4. Schematic diagram of projected next generation small engine.

Table I. Engine specification of projected next generation small engine.

Thrust	8000-12000 lb
Noize	ICAO/Chapter4 -20dB cum
Emmision	ICAO/CAEP4 -50%
Direct Operating Cost	-15%

ICAO:International Civil Aviation organization

then applied to design and manufacture the turbofan F-3 engines for intermediate trainers in the 1980s. Meanwhile, the Ministry of International Trade and Industry (now the Ministry of Economy, Trade and Industry) and the Science and Technology Agency began a project supporting for the research and development of engines for civil use in the 1970s, leading to the development of the first demonstration FJR710 engine. Many test flights had been completed on the Asuka, a jet capable of short- take-offs and landing with the FJR710 engine. The FJR710 engine project was continued as the RJ500 engine development project, pursued jointly by Japan and Great Britain; it then went on to become the V2500 engine project implemented by a five-country consortium. Japan participated in the planning of the latter as a national project. The V2500 was subsequently selected as the engine for the Airbus A320 mid-size passenger jet. To date, more than 5,000 units have been ordered, with Japanese Aero Engines Corporation (JAEC) accounting for approximately 23% of the program. Programs that received financial assistance from the Ministry of Economy, Trade and Industry in the 1990s included the CF34-8 engine (designed for use with regional jets with seating capacities of 70 to 100 passengers) and the CF34-10 engine. These engines entered commercial service in 2001, with Japan accounting for a high 30% of the total. Clearly, Japan has gained international recognitions as a collaborative partner or joint projects RSP (risk revenue sharing partner) of civil engines developments and business, which are increasingly centering on midsize and small engines.

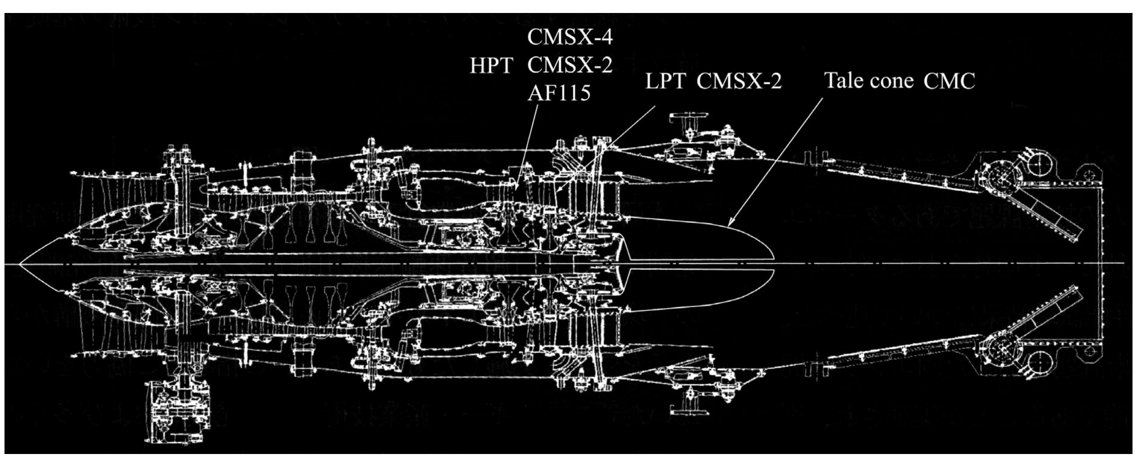
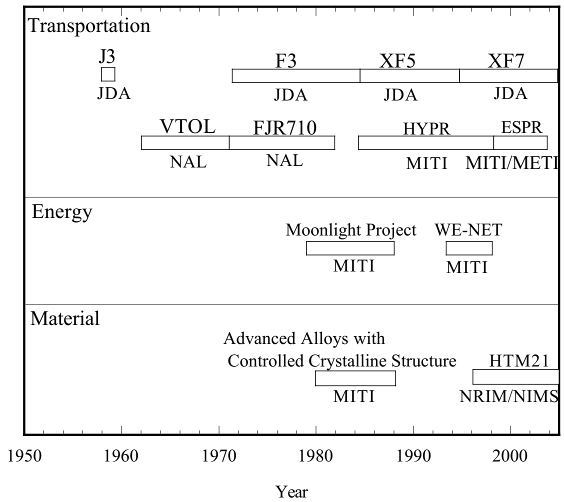


Figure 3. Schematic diagram of HYPR engine and new materials.[2]



JDA:Japan Defense Agency
NAL:National Aerospace Laboratory
MITI:Ministry of International Trade and Industry
METI:Ministry of Economy, Trade and Industry
NIMS:National Institute of Materials Science
NRIM:National Research Institute for Metals

Figure 5. Engines and Material development programs in Japan.

The technical development of engines for next-generation supersonic aircrafts is also moving ahead quickly with governmental programs. The XF5 (a demonstrator engine, a low bypass ratio turbofan with afterburners) and the XF7 (a high bypass ratio turbofan engine) were developed entirely by Japanese engineers. The HYPR (Super/Hyper-Sonic Transport Propulsion System) program was implemented by the New Energy and Industrial Technology Development Organization (NEDO) over a ten-year period beginning in 1989, followed by the ESPR (Research and Development of Environmentally Compatible Propulsion System for Next-Generation Supersonic Transport Project), a five-year program, initiated in 1999. Both research programs focus on engines for use on supersonic aircrafts and involve the collection of data concerning fundamental supersonic engine technologies, including aerodynamics, combustion, cooling, structure and strength, high-temperature materials, system control, fuel efficiency, noise suppression, and the reduction of NOx emissions. Japan has had little experiences on high-pressure turbines, the highest temperature component in international RSP civil engine programs. How-

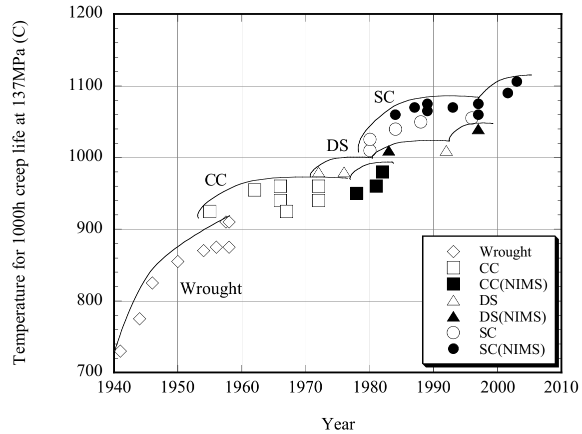


Figure 6. Improvement in temperature capability of Ni-base superalloys.[3]

Table II. Chemical composition of Ni-base superalloys (wt%) [3]

	Alloy	Co	Cr	Mo	W	Al	Ti	Nb	Ta	Hf	Re	C	B	Zr	Ru	Y	Ni
CC	Inconel738	8.5	16	1.7	2.6	3.4	3.4	-	1.7	-	-	.17	.01	0.1	-	-	bal.
	Rene'80	9.5	14	4.0	4.0	3.0	5.0	-	-	-	-	.17	.015	.03	-	-	bal.
	MarM247	10	8.5	0.7	10	5.6	1	-	3	-	-	.16	.015	.04	-	-	bal.
	TM-321	8.2	8.1	-	12.6	5	0.8	-	4.7	-	-	.11	.01	.05	-	-	bal.
DS	CM247LC	9	8	0.5	10	5.6	0.7	-	3.2	1.4	-	.07	.015	.01	-	-	bal.
	PWA1426	12	6.5	1.7	6.5	6	-	-	4	1.5	3	.1	.015	.03	-	-	bal.
	MGA1400	10	14	1.5	4	4	3	-	5	-	-	.08	?	.03	-	-	bal.
	TMD-107	6	3	3	6	6	-	-	6	0.1	5	.07	.015	-	2	-	bal.
SC	CMSX-2	4.6	8	0.6	8	5.6	1	-	9	-	-	-	-	-	-	-	bal.
	Rene'N4	8	9	2	6	3.7	4.2	0.5	4	-	-	-	-	-	-	-	bal.
	PWA1480	5	10	-	4	5	1.5	-	12	-	-	-	-	-	-	-	bal.
	CMSX-4	9	6.5	0.6	6	5.6	1	-	6.5	0.1	3	-	-	-	-	-	bal.
	Rene'N5	8	7	2	5	6.2	-	-	7	0.2	3	-	-	-	-	-	bal.
	PWA1484	10	5	2	6	5.6	-	-	9	-	3	-	-	-	-	-	bal.
	YH61	1	7.1	0.8	8.8	5.1	-	0.8	8.9	0.25	1.4	.07	.02	-	-	-	bal.
	CMSX-10	3	2	0.4	5	5.7	0.2	0.1	8	0.03	6	-	-	-	-	-	bal.
	Rene'N6	12.5	4.2	1.4	6	5.75	-	-	7.2	0.15	5.4	.05	.004	-	-	.01	bal.
	TMS-138	5.8	2.8	2.9	6.1	5.8	-	-	5.6	0.05	5.1	-	-	-	1.9	-	bal.
	TMS-162	5.8	2.9	3.9	5.8	5.8	-	-	5.6	0.09	4.9	-	-	-	6.0	-	bal.

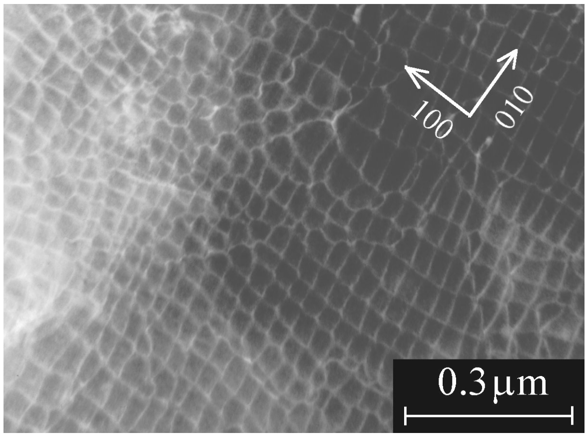


Figure 7. Stable dislocation network on the rafted . and . ’ phasesin a fourth generation SC superalloy TMS-138[4].

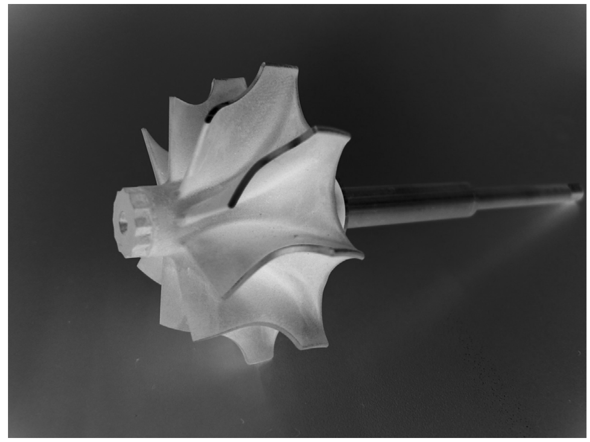


Figure 8. External appearance of turbine rotor made of TiAl.

ever, we are confident that the elemental technologies acquired through the past and current research and development programs, especially heat-resistant materials, cooling technologies, and related processing technologies, make significant contributions for our next engine development like the one for the regional jets.

Research and Development of Materials in Japan

Full-scale development of superalloys and other materials began in Japan as part of multiple national programs aimed at developing gas turbines, including the Moonlight Project (1979-1988, dedicated to researching and developing a high-efficiency gas turbine) and the WE-NET (World Energy Network) Program (1993-1998). The first project dedicated especially to materials development was the Advanced Alloys with Controlled Crystalline Structure Project (1981-1988), through which first-generation single-crystal alloys were developed that did not contain rhenium, along with PM materials and ODS alloys. Most recently, the High Temperature Materials 21 Project (HTM21 Project), conducted by the National Institute for Materials Science (NIMS), has developed fourth-generation single-crystal alloys and DS alloys. Specifically, ruthenium was added to third-generation single-crystal alloys to boost structural stability, resulting in the development of TMS-138, TMS-162 and other alloys that can be considered fourth-generation materials. Among the alloys that have been developed were third-generation single-crystal alloys that, due to the addition of rhenium as a strengthening element, displayed instability on the microstructural level at high temperatures, with an attendant reduction in service life. To improve structural stability at high temperatures, elements such as ruthenium and iridium have been added. Meanwhile, attempts are being made to design alloys by enhancing the formation of a raft structure during deformation and preventing dislocation climbing by optimizing the lattice misfit toward negative (a .<a)[4]. The resulting alloys possess the highest creep strength achieved thus far in the world.

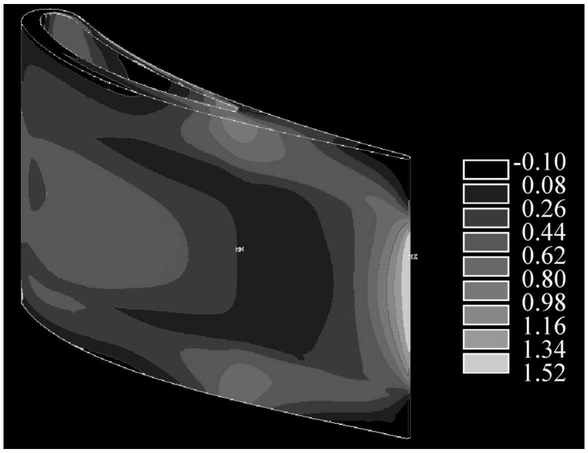
Alloys that can be called third-generation DS alloys have been developed by adding elements to third-generation single-crystal alloys that strengthen grain boundaries [5], thereby producing alloys that have the same strength as the second-generation single-crystal alloy CMSX-4. Recently, fourth-generation DS alloys have also been developed by adding elements to fourth-generation single-crystal alloys that strengthen grain boundaries. These research achievements were achieved through international cooperation and coordination among industry, government and academia under the leadership of the National Institute for Materials Science (NIMS).

Utilizing these basic technologies, private companies are actively developing practical materials for use in gas turbines. Hitachi Ltd., for example, has independently developed a single-crystal alloy called YH61 [6], which features a high tolerance for grains and low-angle grain boundaries, as well as excellent castability and high-temperature strength. Hitachi is also collaborating with The Kansai Electric Power Company and Nagoya University to develop third-generation single-crystal alloys [7], which have promising practical applications.

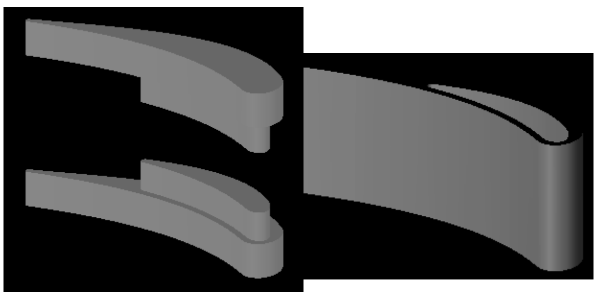
Similarly, Mitsubishi Heavy Industries, Ltd. and Mitsubishi Materials Corporation have independently developed the DS alloys MGA1400 and MGA2400[8]. Designed for use in gas turbines, these alloys contain relatively large amounts of chromium, which provides high resistance to corrosion at high temperatures. MGA1400 has a creep rupture temperature that is about 50°C higher than that of conventional cast materials such as Inconel 738LC, with a thermal fatigue strength approximately 10 times higher.

Alloys being developed are subjected to validation tests through jet engine development projects such as the HYPR and ESPR projects mentioned above. Plans have been made to test TMS-138 and other alloys developed under the above programs on actual aircraft through the jet development programs. In the field of gas turbines, meanwhile, blades made of TMS-75 and TMS-82+ have already been tested in 1300°C-class, 15 MW gas turbines [3, 9]. Another important development are the blades and vanes made of MGA1400 that are currently being used in an actual 1500°C-class large gas turbine.

In the field of thermal barrier coatings, progress is being made in



(a)



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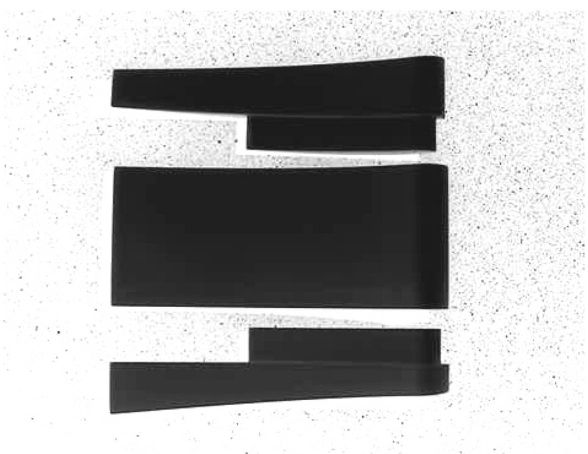


(c)

Figure 9. MGC turbin nozzle. (a)Results of thermal stress analysis. Generated stress is non-dimensionalized by allowable stress.), (b)Improvement of nozzle shape-separated hollow nozzle. (c) Actual turbine nozzle.[13]

the national NEDO Nano-Coating Technology Project. This project is dedicated to developing TBC that uses EB-PVD equipment to control material structure on the nano level [10]. Because coatings produced through the EB-PVD method usually have a finer structure than sprayed coatings, heat conductivity has been a problem. This problem was solved by introducing nano pores into the coating, but other difficulties remain, including the fact that the EB-PVD method takes longer to form a coating layer than spraying does, and has a relatively large effect on the surface form being coated. For these reasons, the EB-PVD technology must be further improved.

Progress is also made on the development of TiAl alloy that can be used in a temperature range between those of Ti alloys and superalloys. Successful demonstration tests have already been completed on actual engines. In 1995, ground engine, CF6-80C2, tests were performed with LPT#5 blades cast from the TiAl alloys, GE48-2-2 developed by GE, along with Alloy01A developed by Ishikawajima-Harima Heavy Industries (IHI) [11]. These alloys feature a duplex structure composed of a lamellar structure and . grains, which sacrifices high-temperature strength for greater ductility at room temperature. Subsequently, other alloys were developed, including a TiAl alloy with a full lamellar structure for high high-temperature strength, and as well as an alloy with higher high-temperature plasticity that makes iso-thermal forging possible into bar, sheet, and blade shape. Some of the TiAl alloys are also already in actual use in applications other than aero engines, such as in the impellers of automotive turbochargers as shown in Figure 8 [12].

Progress is also being made in the ceramic material technologies. As a part of the ESPR program, a composite afterburner flaps manufactured with a heat resistant CMC (Ceramic Matrix Composite) layer on top of lightweight TiAl supports were engine-tested successfully.

In recent years, materials called MGCs (Melt-Growth Composites) made by directional solidification of eutectic oxide melts, for example $Al_2O_3/Y_3Al_5O_{12}$, have been developed that can maintain high strength at temperatures up to 1,700°C and are also highly resistant to oxidation promising a significant reduction of the sys-

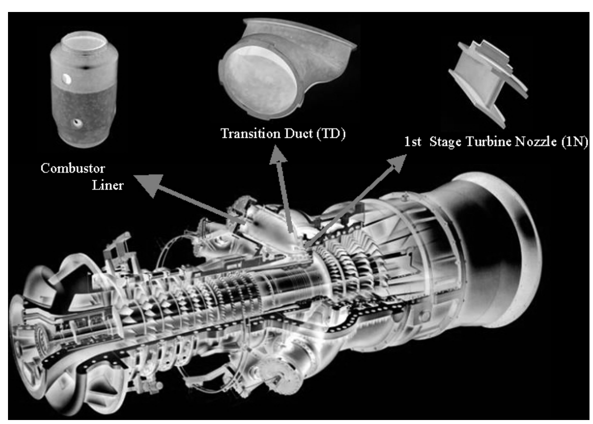


Figure 10. Schematic diagram of hybrid gas turbine and some parts made by ceramics. [15]

tem cooling air [13]. However, unlike Si_3N_4, higher thermal stresses are generated in the Al_2O_3-based ceramics components due to their low thermal conductivity and high thermal expansion, and high Young's modulus, requiring some design consideration. To address this issue, prototype MGC turbine blades have been manufactured as part of the "Research and Development Project on MGC Ultra-efficient Gas Turbine Systems," implemented by the Ministry of Economy, Trade and Industry, and NEDO in 2001. A hollow nozzle shape was optimized to minimize the thermal stress distribution by numerical analyses[14]. Hot gas tests were conducted to measure span-wide temperature distribution on MGC model nozzles, and a three-pieces-separated nozzle was designed as shown in Figure 9.

Another goverment project for ceramics application for gas turbines, was initiated in 1999, in which 1st stage HPT nozzles, combustor liners and conbustor ducts made by Si_3N_4 were successgfully tested in the Kawasaki M7A, 8MW gas turbine. A schematic is given in Figure 10. It is generally accepted for those ceramics application that compatibility with existing metals components remains to be a major technical issues.

Unique manufacturing technologies have also been developed in recent years. Many high-temperature components require special surface coating by galvanization, welding and thermal spray that prevent wear and oxidation. One alternative method is called Micro Spark Coating, in which any ceramics or metals can be deposited on the component surfaces through electrical pulses arc. This technology was developed jointly by IHI and Mitsubishi Electric Corporation. Figure 11 shows the principal of Micro Spark Coating and microstructures of coating layer. Because the process does not require expensive hardware investment and can be easily incorporated in existing production lines, it is expected that the technology makes a significant economic contribution in various coating process industries, especially in aerospace-related fields. Another technology that has emerged from the same type of process developments is three-dimensional plastic working for stationary compressor vanes. This is a rolling and press forming by rolls technology developed along with machining jigs, mold design, shape measurement and evaluative technologies, and mass- application is within sight.

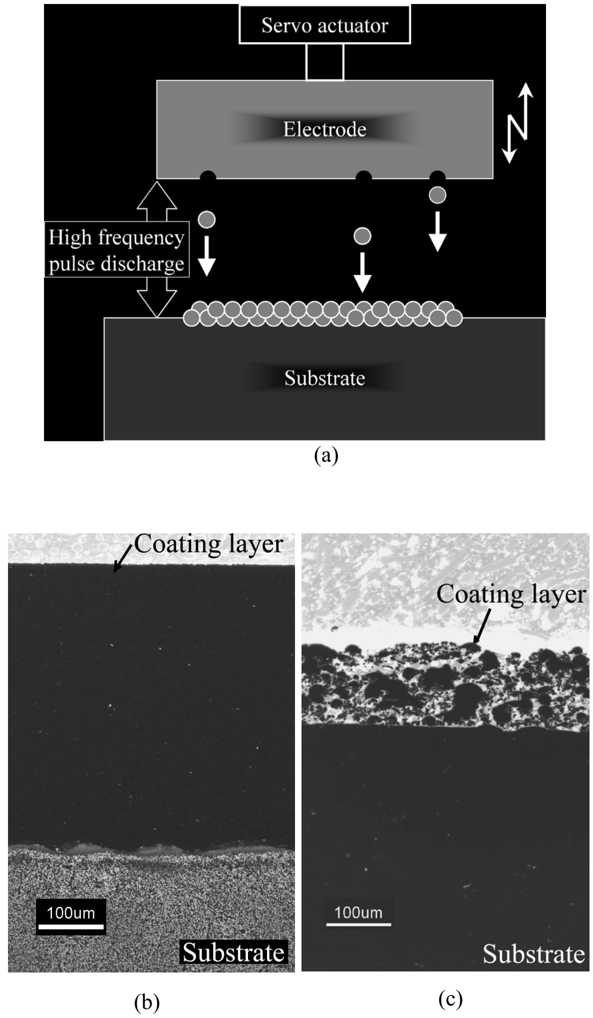


Figure 11. (a) Basic principal of Micro Spark Coating and various microstructures of coating cross section (b) dense coating, (c) porous coating.

Future Prospects for Superalloys

Ni-based alloys melt at around 1350°C, and dramatic improvements in heat resistance have proven elusive. Still, compared with new materials that have been developed as alternatives, Ni-based alloys remain highly competitive today in overall terms of such factors as heat resistance, ductility, toughness and cost. While efforts continue to be made to improve heat resistance through materials development, improved production processes, and TBC development, etc., Ni-based alloys are expected to remain leading structural materials for some time to come.

Focusing on the development of superalloys, two trends can be discerned: the continued search for improved heat resistance, and the development of highly economical alloys. That is, development will focus on alloys that provide a good yield or that make it possible to simplify the manufacturing process. This paper examines the future research and development of superalloys from the perspectives of both increased strength and better economic viability.

Higher Strength and Heat Resistance

Demand will continue for stronger jet-engine materials that allow faster revolution speed, and that have greater heat resistance to allow higher combustion temperatures.

In the field of single-crystal alloys, much work is being done on the development of stronger alloys [4,16-20]. However, as more use is made of alloys containing high levels of refractory elements, problems such as segregation and incipient melting during heat treatments have become more pronounced. To avoid these problems, more complex manufacturing processes are necessary, which raises the cost. In the field of single-crystal alloys for gas turbine use, efforts are being made to simplify manufacturing [3]. In the future, single-crystal alloys that can be used in uncooled, medium-pressure jet-engine turbines at a temperature of 1000°C will be the focus of considerable attention; the objective is to develop an alloy that has a large heat treatment window and that will not complicate the manufacturing process.

In contrast, relatively little energy is being put into the development of new materials for high-pressure turbines. The mitigation of TBC-induced metal heat and oxidation resistance coatings continues to be an important goal. It has been reported that, in third-generation materials, a reaction between the oxidation resistance coating and the base material creates a reaction zone on the base-material side that reduces high-temperature strength [21]. Thus far, there has been little technical collaboration between coating development and single-crystal development. In fact, almost no effort has been made to develop coatings that will not compromise the mechanical properties of single-crystal alloys, or to develop alloys that retain their mechanical properties during the coating process. Greater emphasis is likely to be placed not only on finding ways to strengthen the base material, but also on designing alloys whose material quality will not be degraded because of coatings.

With respect to increasing the strength of materials used in forging, efforts to strengthen materials by developing new alloys will continue, in tandem with efforts to reduce scattering data and increase the design allowable stress. To reduce defects, inclusions, and non-uniform structures that contribute to data spread, the VIM-VAR double-melt system is giving way to the VIM-ESR-VAR triple-melt method, which improves ingot purity [22-26]. It is difficult to achieve an uniform structure in large-diameter ingots, and there is demand for greater metal-structure soundness as ingot size increases. Currently, much research is being conducted on the relationship between melting conditions and ingot structure, and the development of melting methods that produce a uniform structure is likely to progress.

In another development, powder metallurgical alloys will increasingly be used in the manufacture of turbine disks, which until now have been made through melting/forging methods. Powder metallurgical alloys produce a uniform metal structure free of segregation, which helps increase strength through the greater use of high alloys. Furthermore, they are amenable to iso-thermal forging and other near-net shape processes, which gives them a high material yield. However, it is extremely difficult to prevent inclusions from entering when alloy powder is processed, resulting in reduction of low cycle fatigue strength and other irregularities [27]. Therefore, assuming that inclusions are unavoidable in powder metallurgical alloys, materials are being designed so as to minimize the speed of crack development, and damage-tolerance design methods are being used for powder metallurgical disk mate-

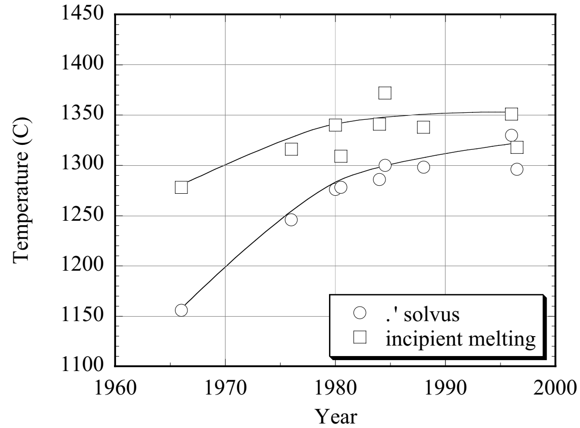
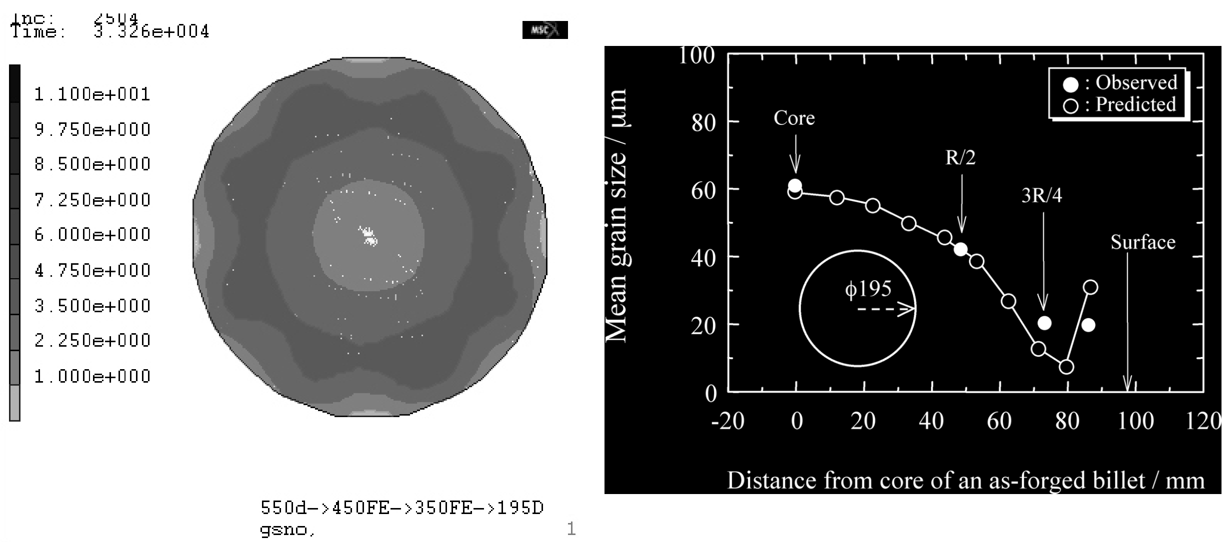


Figure 12. Heat treatment window of various Ni base superalloys.



(a) (b)

Figure 13. Process modeling for radial forging of Inconel 718. (a) contour diagram of grain size during forging from 550 to 195 mm in diameter. (b) accuracy of predicted grain size in cross section.[33]

rial [28]. This damage-tolerance design assumes that initial defects exist, and that the service life of the material is a function of the speed with which cracks develop from those defects. This design method increases the allowable stress in comparison with materials that are designed on the basis of low cycle fatigue strength.

Improvements in Process Simulation Technologies

In addition to increasing strength, economic viability is crucial in the development of materials technologies. Material costs account for a large share of the total cost of engine manufacture, and so these costs, including the cost of material development, must be reduced. Process simulation offers one way to reduce material costs, and the greater use of simulation technologies is improving economic viability by shortening the material development time and increasing the yield. In the field of casting, for example, a technology has been developed that predicts the structure of single crystals and directionally solidified material [29]. When investigating casting methods, this technology makes it possible to predict the position of casting defects and the occurrence of grains. In the future, as higher-temperature gas turbines come into use, larger single-crystal blades and vanes and directionally solidified blades and vanes will be unavoidable. As the size increases, the solidification process will take longer, and this is expected to cause segregation problems. Segregation, which causes partial melting and otherwise complicates the heat treatment process, also affects material strength. It is therefore important to develop means of predicting casting defects and grains, as well as predicting segregation on both the macro and micro level, in order to improve the yield and simplify the heat treatment process. Also, as jet engines and gas turbines increase in size, so does the size of castings, which means larger feeding heads. Through the introduction of casting simulation technology, it will be possible not only to lower costs by reducing the number of rejected castings through defect prediction, but also to reduce the number of trial castings, and minimize material consumption by optimizing the shape of the feeding head.

When forging disk material, the material is first die forged into an approximate shape and then further worked to obtain the final form, resulting in huge quantities of scrap. By building a simulation system that calculates the near-net shape while taking into account deformation resulting from the forging process, the material yield can be raised. Currently, we have data on simulations concerning the distribution of grain diameters and obtainable strength achieved through die forging or radial forging [30-33], but further progress in this technology is desired.

As with simulations of cast products, much research is underway on simulating the solid structure of ingots [34]. In large ingots, the addition of Nb (niobium) and other strengthening elements makes it difficult to achieve a sound metal structure. Studies are needed on ways to utilize solidification simulations to prevent white spots, freckles and other defects in order to boost material yield.

Advances in computer science have also been spectacular in manufacturing technologies other than those used in material manufacture. One example is material evaluation through virtual gas-turbine operation [35]. Also, recent advances in 3D CAD technologies have made it possible to conduct virtual manufacturing on computers, thus reducing the time needed for the manufacturing side to provide feedback to the design side. This technology greatly reduces the trial manufacturing cycle and hence the cost.

Similarly, advances in NDE (nondestructive evaluation) technologies have made it possible to identify the three-dimensional position of inclusions in billets, so that only those sections of the billets that contain inclusions need be removed while preserving the sound portions, and so reducing costs substantially.

Conclusion and Prospects

If Japan is to claim its place as a firm player in the international engine business, it must successfully and continuously develop and mass-produce its original engines. The Japanese have relatively little experience in manufacturing parts for high-pressure, high-temperature turbines in civil engines, which means it is crucial for them to establish their own design and production technologies for heat-resistant components. This will require the wide-ranging research and development foundation spanning from basic science through to practical applications in superalloys for which effectiveness of international collaborations and links among industries, government and academia has been historically proven. In business, Japan will increase its roll as a production service provider of critical components for the engine manufactures in the US and Europe. The shift toward repair and maintenance services will also accelerate. In the long-term, task-sharing-alliances in business will likely develop in the Asia countries, regionally specializing tasks such as design, component production, assembly, and materials.

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