Development of Turbocharger for Next-generation Hybrid Electric Vehicles

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In recent years, with the great efforts toward carbon neutrality as a measure against global warming, it is predicted that the share of hybrid electric passenger cars will increase. The operating range of internal combustion engines for hybrid electric vehicles is limited compared with conventional ones and turbochargers are also required to be developed to address this limitation. Mitsubishi Heavy Industries Engine & Turbocharger, Ltd. (MHIET) has developed high-efficiency compressors that meet the requirement of hybrid electric vehicles, vaned nozzle turbines designed for higher efficiency, ball bearings designed to reduce mechanical loss and low-cost turbine housing materials that are designed by using data science and has been proposing to automobile manufacturers.

1. Introduction

As a countermeasure against climate change caused by global warming in recent years, efforts toward carbon neutrality have been accelerated in various countries around the world. In the automobile industry, CO_2 emissions regulations are planned to be tightened and in Europe, the regulations are expected to be tightened by 2030, in which the regulation value will be reduced by 37.5% compared with that in 2021. Due to this tightening of regulations, the introduction of vehicles with lower CO_2 emissions (plug-in hybrid electric vehicles (PHEV), battery electric vehicles (BEV), fuel cell electric vehicles (FCEV), etc.) is being promoted in various countries and sales of internal combustion engine vehicles will be prohibited in European countries by approximately 2030 to 2040. On the other hand, reserves of raw materials (lithium, nickel and cobalt) for batteries installed on electric vehicles are limited and it is difficult with current battery technology to realize a scenario of converting all vehicles to electric vehicles. There is also another problem in that electric vehicles cannot be considered as zero CO_2 emissions unless they are used in areas where renewable energy power generation has become widespread. One possible realistic scenario is to continue to produce automobiles equipped with a lower-fuel consumption internal combustion engine with its operating range limited by using a hybrid system while promoting the spread of BEVs, like the proposal made in the "Energy Saving and New Energy Vehicle Technology Roadmap 2.0" announced by the China Society of Automotive Engineers (SAE-China) last year. **Figure 1** shows the hybrid electric vehicle systems that are expected to become widespread in major global markets. In Europe, the United States and China, parallel mild hybrid electric vehicles with a 48 V power supply are expected to become the most popular. On the other hand, in the Japanese market, due to the fact that hybrid electric vehicles have been mass-produced ahead of other countries, it is expected that power split strong hybrid electric and series strong hybrid electric vehicles will occupy a large share. In order to respond to this technological trend,

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we are developing turbochargers which matches to the internal combustion engine installed on hybrid electric vehicles. This report describes the development status.

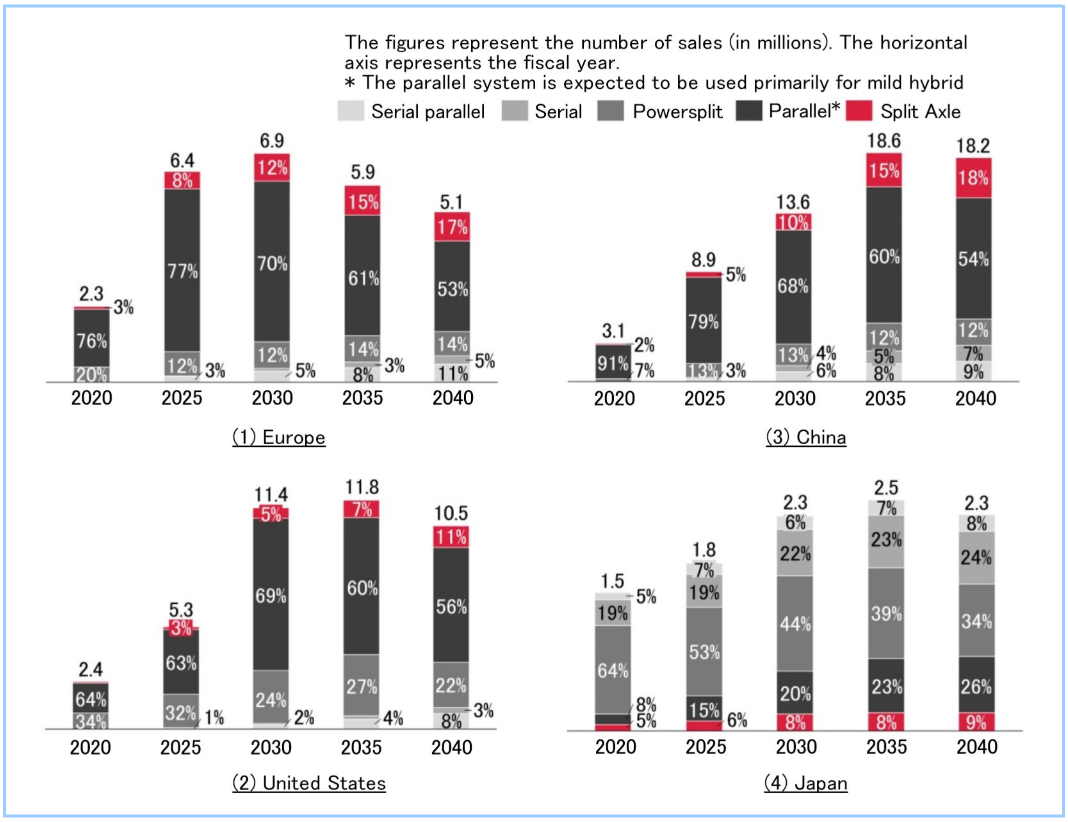

Figure 1 Comparison of share of hybrid electric vehicle systems in major markets (according to FEV Consulting GmbH)

2. Changes in performance requirements for turbochargers due to use of hybrid system

Vehicle hybrid systems are roughly classified into a parallel hybrid system that uses both a motor and an engine to drive the vehicle and a series hybrid system that uses a motor only to drive the vehicle and an engine dedicated only to electric power generation. (A power split system distributes the engine output for driving and electric power generation and is classified as an intermediate between the parallel system and the series system. The turbocharger operating point of the power split system is close to that of the series system, so its explanation is omitted in this report.)

The parallel hybrid system uses the engine as the main driving power source and the motor as the sub driving power source to produce the driving force required by the vehicle, in order to set the engine operating points within a high-efficiency range and improve the vehicle fuel efficiency. For example, when the vehicle is running at a low speed, the engine is stopped and the vehicle is driven only by the motor in order to avoid low-load engine operation, which is inefficient. When the vehicle is quickly accelerating, the engine is assisted by the motor in order to use a high-efficiency middle-torque range and improve the vehicle fuel efficiency. **Figure 2** illustrates, on a conventional downsized turbocharged engine torque diagram, the engine operating range that is not used when the vehicle is driven only by the motor and the engine operating range that is not used when the engine is assisted by the motor. Changes in the full load operating points of the turbocharger compressor in this case are shown in **Figure 3**. The compressor pressure ratio at low flow rate operating points is reduced by the reduction of the maximum required torque at low engine speeds and the maximum flow rate is also reduced by the suppression of the maximum output. Due to the reduced required torque at low engine speeds, it is possible to use a large-capacity turbine that focuses on high engine speed and high output, so the improvement of the turbine efficiency and fuel efficiency during high-speed running in which the engine is used as the main power source is expected.

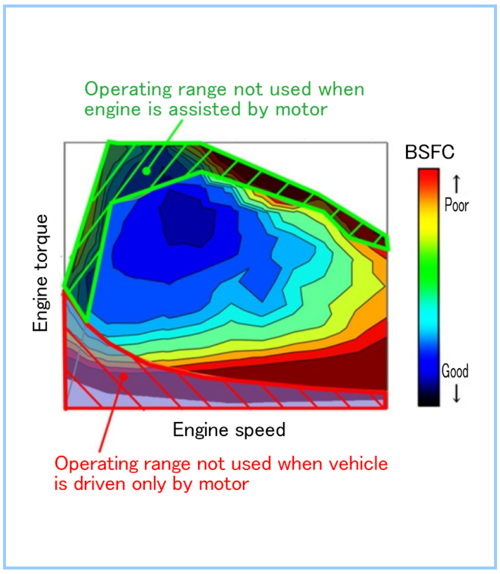

Figure 2 Operating range of engine installed on parallel hybrid electric vehicle

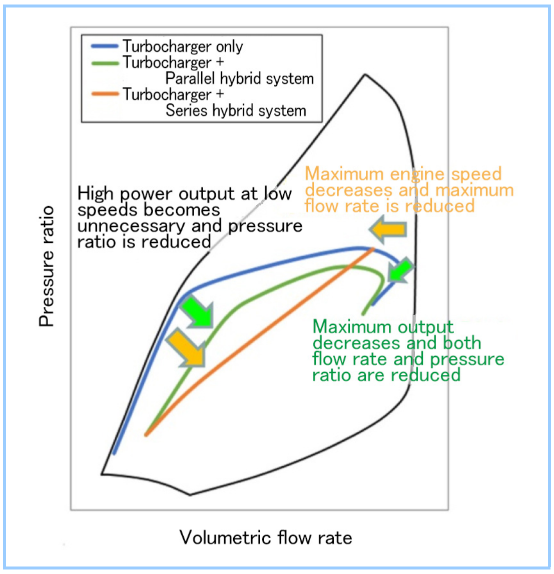

Figure 3 All-load operating points of compressor for hybrid system

On the other hand, the series hybrid electric vehicle uses the engine only for electric power generation, so the most fuel-efficient operating range can be used for producing the required output without depending on the engine speed. **Figure 4** shows, on a conventional downsized turbocharged engine torque diagram, operating points of an engine installed on a series hybrid electric vehicle. For a conventional downsized turbocharged engine, plane operating range area is required. However, in the case of a series hybrid electric vehicle, its operation can be changed a line. Changes in the full load operating points of the turbocharger compressor in this case are shown in Figure 3. Since only operating points with good engine fuel efficiency are used, the operating ranges of both the compressor and turbine are narrowed.

As described above, when a hybrid system is adopted, the operating ranges of the engine and turbocharger tend to be narrowed for the purpose of reducing fuel consumption. Due to the narrower operating range, it is expected that the efficiency of the turbocharger can be improved. The following chapters explain the efficiency improvement of components: the compressor, turbine and bearing.

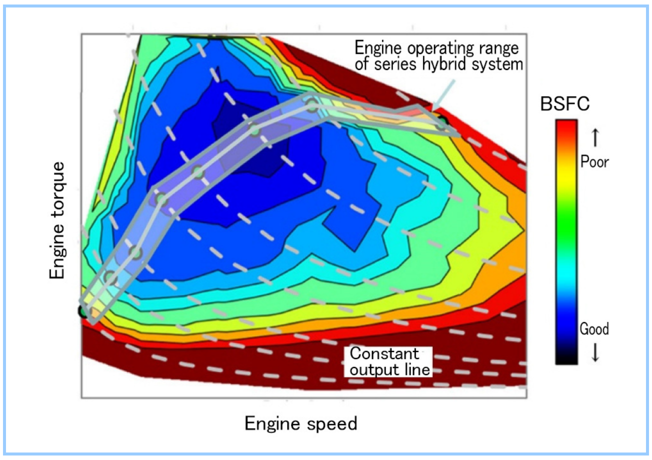

Figure 4 Operating range of engine installed on series hybrid electric vehicle

3. Improvement of compressor performance

In the past, centrifugal compressors used for passenger car engines were required to have high performance in the medium and high specific speed ranges, so designs for reducing secondary flow loss and separation loss by using three-dimensional impellers and optimization of blade loading have been considered[(1)(2)]. However, engines for hybrid electric vehicles, which have been rapidly developed in recent years, require higher efficiency of low specific speed centrifugal compressors that do not have a wide operating range. Therefore, we worked on the development of a high-efficiency centrifugal compressor that reduces friction loss and mixing loss, which are the main loss structures in the low specific speed range.

Figure 5 is an appearance of the new designed centrifugal compressor. With the assumed operating points of the hybrid electric vehicle engine as the design points, the inlet design of this compressor was optimized to reduce leakage flow, shock waves and collision loss, while the outlet was designed to reduce wake, mixing loss and downstream friction loss. **Figure 6** gives the performance test results. This figure shows that the new designed centrifugal compressor has achieved higher efficiency.

Figure 5 Appearance of high-efficiency centrifugal compressor

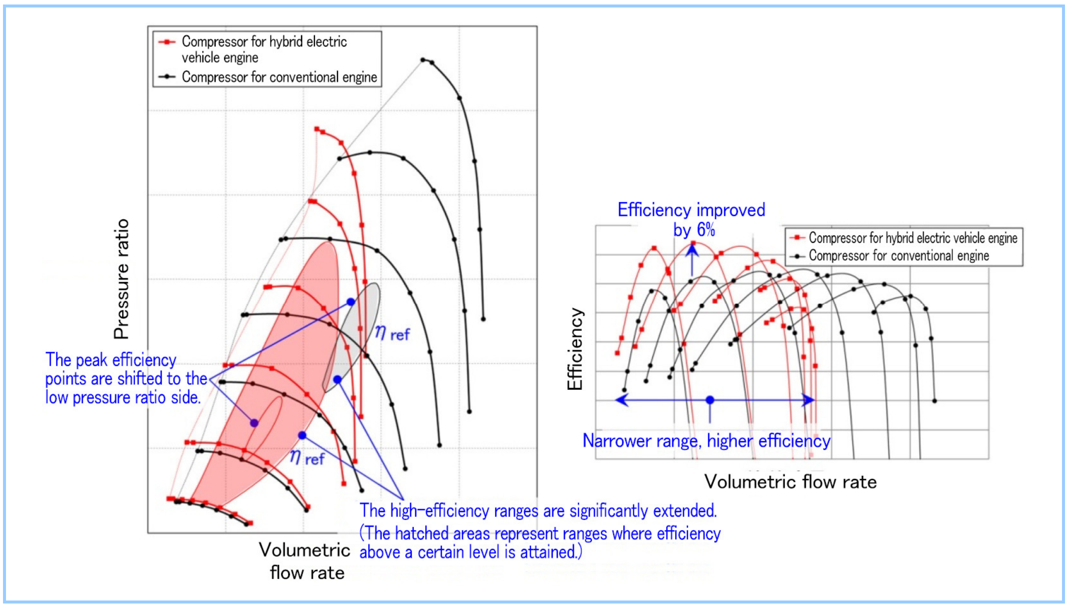

Figure 6 Performance test results of newly designed compressor

Figure 7 plots the performance test results of our centrifugal compressor on a chart with the specific speed on the horizontal axis and the maximum efficiency on the vertical axis. This figure shows that the new designed compressor has achieved significantly higher efficiency in the low specific speed range. Based on this compressor, we will try to improve the efficiency by applying a vaned diffuser with stator blades therein and optimizing the blade shape in the future.

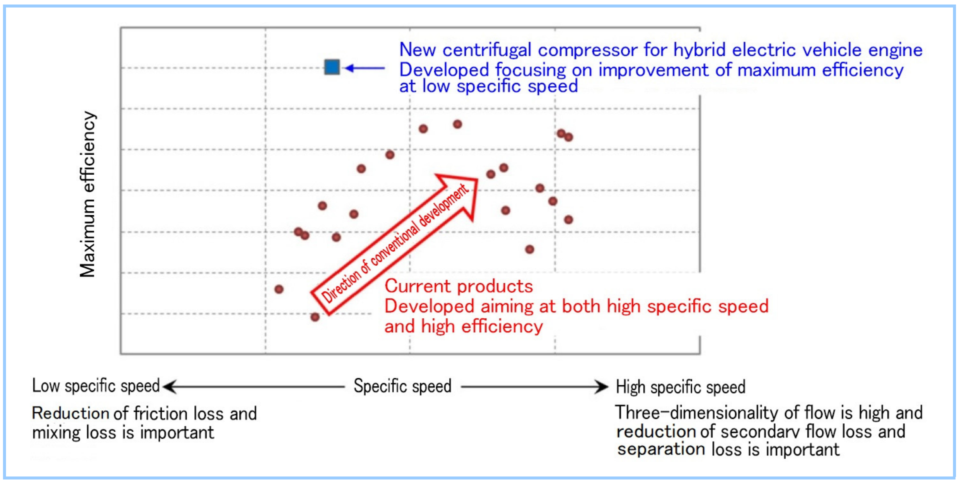

Figure 7　Specific speed and maximum efficiency

4. Improvement of turbine performance

Today's turbochargers for passenger cars have used vaneless nozzle turbines with no stator blades in the flow path for guiding exhaust gas to the rotor blade and variable vaned nozzle turbines that can adjust the turbine flow rate with variable stator blades, in order to adopt the wide operating range. On the other hand, engines installed on hybrid electric vehicles, especially series hybrid electric vehicles, are required to have higher performance while its operating range is significantly limited. In order to manage such a requirement, a vaned nozzle turbine with stator blades in the flow path for guiding exhaust gas to the rotor blade, which are used in power generation diesel engines, is optimal.

Figure 8 presents an appearance of the vaned nozzle turbine designed for hybrid electric vehicles. One of the remarkable of this turbine is that there are stator blades between volute passage (scroll) and the rotor blade for turning the exhaust gas flow. The stator blades reduce the flow deviation in the scroll circumferential direction and form the optimum flow for the rotor blade in order to improve the efficiency. At the same time, the expansion of exhaust gas is performed mainly on the vaned nozzle to reduce the friction loss in the scroll. In addition, since the stator blades of this turbine are not moved, it is possible to set the clearance at the tip of the stator blade, which is adopted for variable vanes of variable geometry turbine to avoid vane stick, to zero and thereby improve the efficiency.

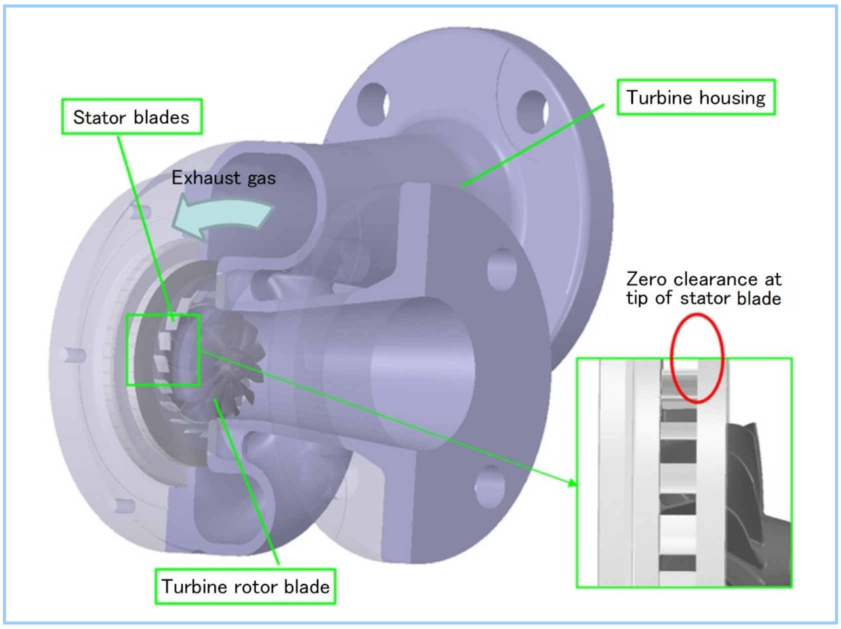

Figure 8　Appearance of vaned nozzle turbine

Figure 9 shows the improvement in the aerodynamic efficiency of the vaned nozzle turbine compared with that of a vaneless nozzle turbine. Adoption of the vaned nozzle turbine enables to have the better turbine efficiency by about 10%. One of the other advantages is the design flexibility with which the efficiency can be further improved by customizing the nozzle vane opening, shape and blade specifications according to the targeted required operating point.

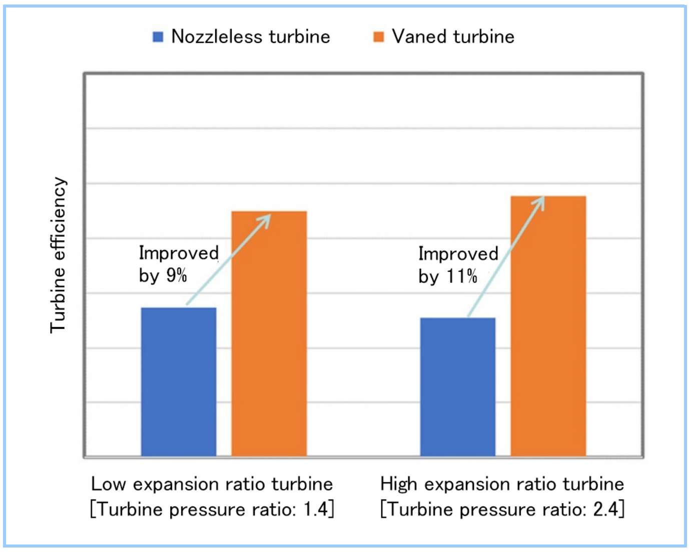

Figure 9 Improvement in aerodynamic efficiency due to adoption of vaned nozzle turbine (Comparison of pure aerodynamic efficiency)

5. Improvement of bearing system

Since a hybrid electric vehicle does not use the low load range of the engine, in which the fuel efficiency is poor, the engine operates a rapid load increase when restarted after idling stop. According to this operation, the turbocharger rotation speed also rising rapidly, causing a delay in lubricating the turbocharger. As a countermeasure to this, we considered the adoption of ball bearings that can be used in no oil supply conditions. **Figure 10** shows the cross-sectional view of it.

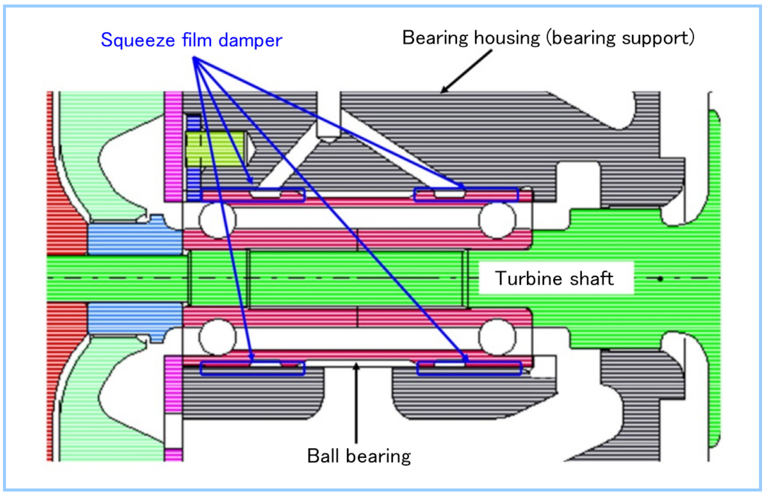

Figure 10 Cross-sectional view of ball bearing

Ball bearings have the advantage of low mechanical loss compared with the floating bearings used in conventional turbochargers, but have a risk of reduction in the vibration damping, increase in the shaft vibration and worsening the noise level. Therefore, we designed and applied a squeeze film damper between ball bearing and bearing housing in order to improve vibration damping. **Figure 11** shows the mechanical loss measurement result and the turbocharger efficiency test result. It shows that the adoption of the ball bearing reduced mechanical loss by about 50% (at 120 krpm) and the turbocharger efficiency is improved by about 2% over the entire operating range.

Figure 12 shows the turbocharger housing acceleration measured as an alternative value for shaft vibration and turbocharger noise. In this figure, it shows that the turbocharger can operate up to the rated rotation speed without a sudden increase in the acceleration along with an increase of the turbocharger rotation speed. It can also be seen from this figure that there is almost no difference between acceleration data before and after the 250-hour durability test.

We validated that the ball bearing has less mechanical loss than conventional floating bearing and has no problem in terms of the vibration characteristics. In the future, we will expand the model variations based on these specifications.

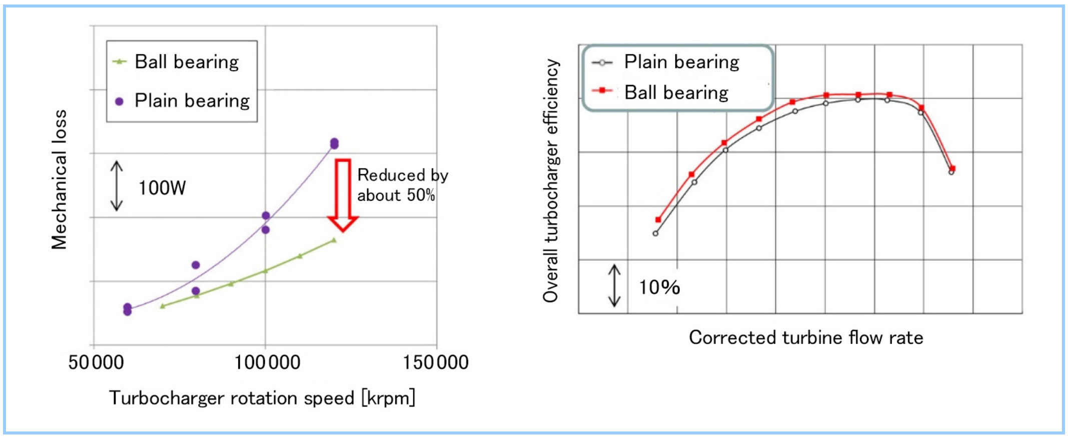

Figure 11 Comparison of mechanical loss and overall turbocharger efficiency between plain bearing and ball bearing

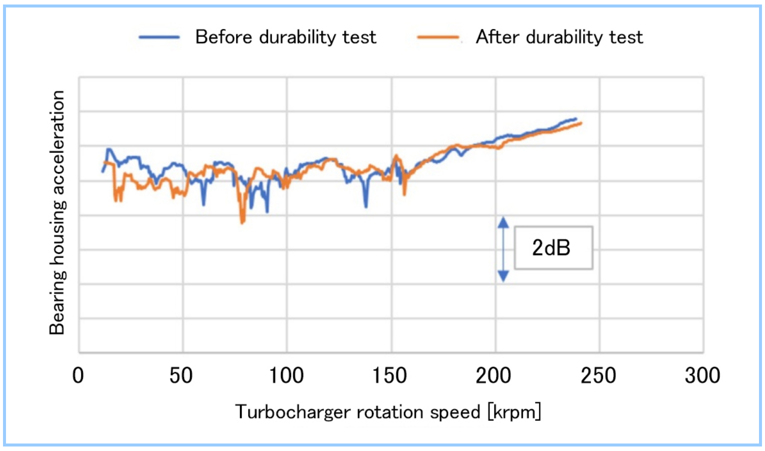

Figure 12 Comparison of turbocharger vibration acceleration before and after durability test

6. Development of materials

Hybrid electric vehicles have additional parts like a motor, inverter, battery, etc. compared with conventional passenger cars, and it have high production costs. Therefore, the price of the engine including the turbocharger needs to be reduced and it is indispensable to reduce the cost of the turbine housing, which function is turning the exhaust gas flow by scroll and is the costliest parts among the turbocharger components. We use austenitic stainless heat-resistant cast steel providing DIN standard* as our standard material for the turbine housing of turbochargers for gasoline engines (**Figure 13**). Due to the countermeasure of high temperature exhaust gas requirement from the customer, DIN materials (1.4848 and 1.4849) containing a large amount of expensive nickel have to be used, resulting in high cost.

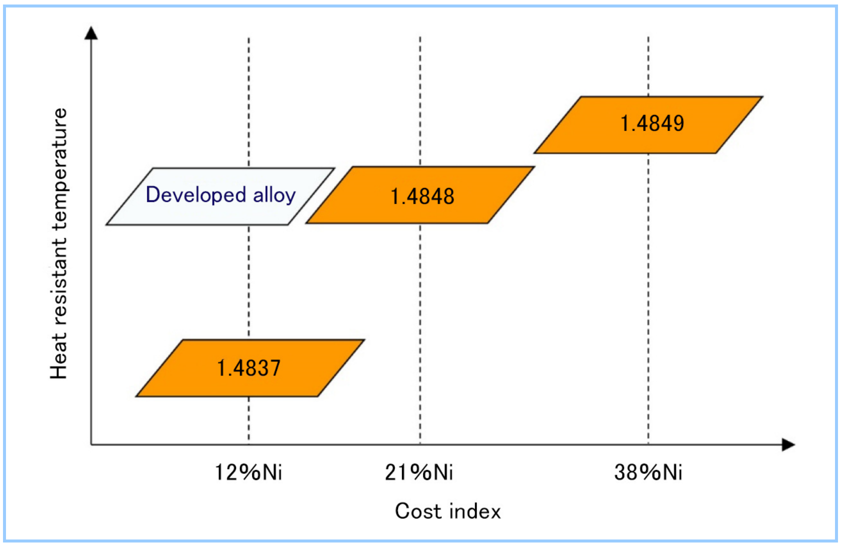

Figure 13 Heat resistant temperature and Ni content of austenitic stainless cast steel conforming to DIN standard

In collaboration with Alloyed, which conducts heat-resistant alloy materials design business, etc., we have developed a low-cost turbine housing material with material properties equivalent to the 1.4848 material using Alloys-by-Design, ABD®, a computational material design technology owned by Alloyed. **Figure 14** shows the alloy design procedure for the low-cost turbine housing material. This method can estimate material properties from the combination of the relationships of the chemical composition, material composition and material properties with databases and computational engineering, facilitating the design of alloys in a shorter period of time and at a lower cost compared with conventional trial-and-error or experimental approaches. After estimating the performance of all alloys that can be combined within a wide range of chemical composition of austenitic stainless steel, we selected chemical components that are cheaper than 1.4848 material and have the same material properties thereof (high-temperature strength, structural stability and oxidation resistance). **Figure 15** is an example of the prototype material test results of the two designed candidate alloy materials. It was confirmed that the materials have the same or higher high-temperature strength than the 1.4848 material and that the material cost can be reduced by about 10 to 30%. In the future, we will evaluate the castability and machinability of the candidate material into the turbine housing shape and also conduct durability evaluation according to the operating conditions of the engine in order to apply the material to series production.

* DIN standard: National standard of the Federal Republic of Germany established by Deutsches Institut für Normung

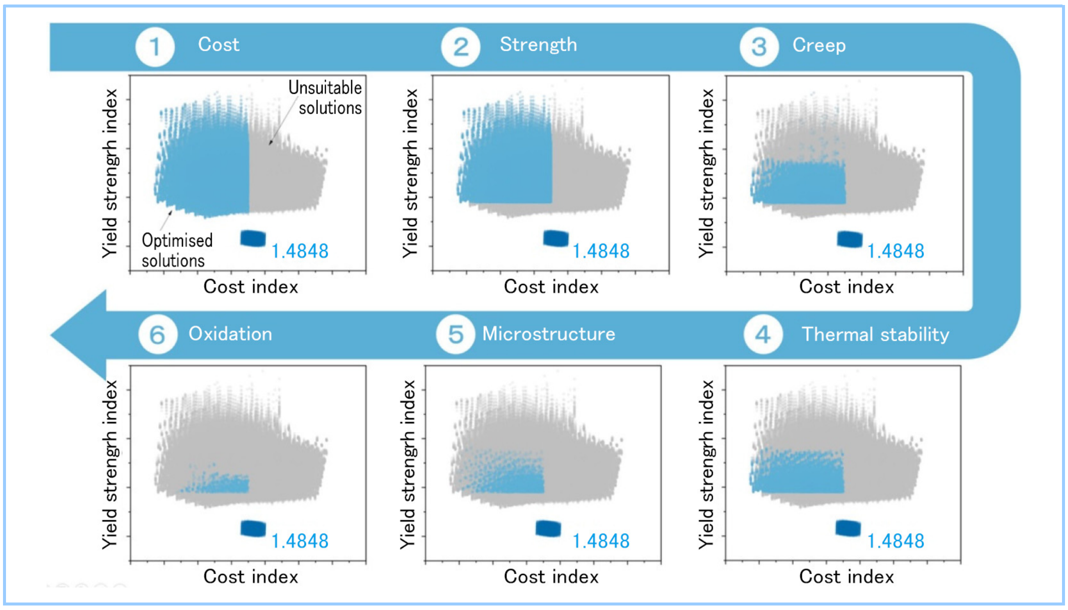

Figure 14 Alloy design procedure for low-cost turbine housing

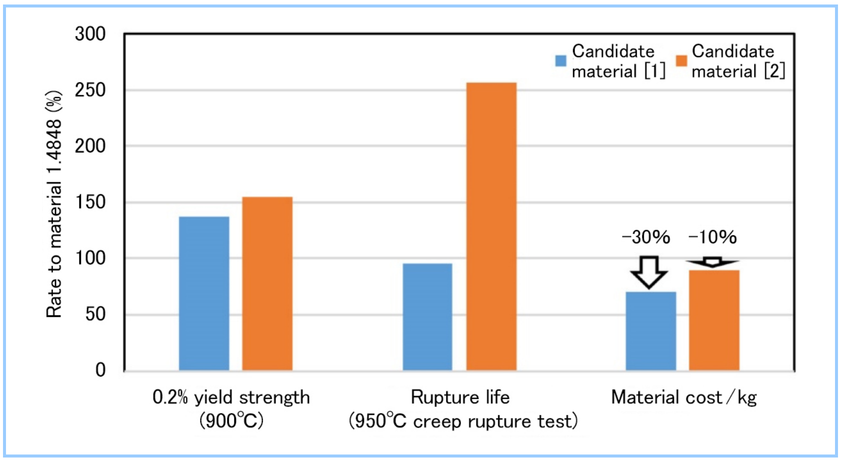

Figure 15　Material test result of prototype

7. Conclusion

This report provided an overview of changes of the requirement for turbocharger due to the adoption of a hybrid system and described the newly developed high-efficiency compressor, vaned nozzle turbine, low-mechanical-loss and low-noise ball bearings, as well as low-cost turbine housing materials as technologies to be applied to turbochargers for next-generation hybrid electric vehicles. In recent years, attention to electric vehicles that do not have an internal combustion engine has been increasing. However, there are still many technical issues to be solved and we believe that internal combustion engines will continue to play an important role in the future. Turbochargers can greatly contribute to reducing the fuel consumption of such internal combustion engines. In the future, we will continue our efforts to improve the global environment by striving to spread the technologies described in this report in cooperation with automobile manufacturers.

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