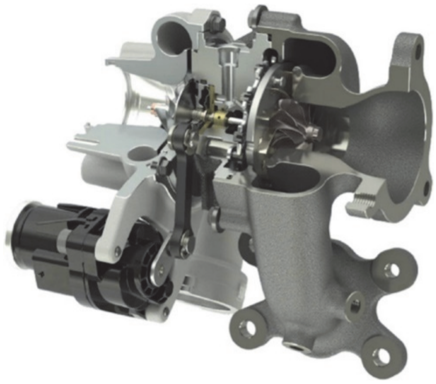
Reliability Improvement of Next-Generation VG Turbocharger for Gasoline Engines



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To achieve decarbonization as a countermeasure against global warming, the trend toward electrification has been accelerating in the automotive industry. However, the spread of electric vehicles and fuel cell vehicles requires the development of cost-reducing technologies and infrastructure improvement. Mitsubishi Heavy Industries Engine & Turbocharger, Ltd. is developing turbochargers that meet the required characteristics of hybrid vehicle engines in various regions. This report describes turbocharger development.

1. Introduction

In Europe, engine development for the Euro 6d standards started around 2015, and the evaluation test methods for exhaust gas and fuel consumption were revised. This led to a shift from downsized turbocharged engines, which had been the mainstream up to that point, to engines with more appropriate displacement and Miller cycle engines. As a means to compensate for the lack of low-speed torque of Miller cycle engines, variable geometry turbochargers (hereinafter referred to as VGT) for gasoline engines appeared on the market. Also in China, development toward China 6a standards, which are similar to Euro 6d standards, started around 2018, and the need for VGTs emerged. As described in Reference (1), Mitsubishi Heavy Industries Engine & Turbocharger, Ltd. (hereinafter referred to as MHIET) also developed a VGT for 1.5-liter engines for the European and Chinese markets and launched it in 2020. Subsequently, after a shift to the development of electric vehicles in Europe and China, the development of strong hybrid and plug-in hybrid vehicles has been increasing again in recent years. However, as the operating range of the motor widens and the operating range of the engine narrows, there is a move from VGTs to turbochargers with less expensive mechanisms, and MHIET is developing such products as shown in Reference (2). On the other hand, in North America, the federal government and the State of California will tighten their emission regulations in 2027, and engine development (adoption of a mirror cycle) has been active since 2024. In particular, the development of 2.5- to 3.5-liter engines for large passenger cars (1,600 kg or more), the electrification of which is problematic in terms of cruising range, is rapidly increasing. Accordingly, turbocharger manufacturers are increasing the size of VGTs originally developed for 1.5- to 2.0-liter engines for the European and Chinese markets targeting the U.S. market. MHIET is working to improve the reliability and reduce the cost of VGTs as well as to increase their size. This paper introduces MHIET's efforts on improved-spec VGTs and cost-saving-spec VGTs defined below.

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Current production-spec VGTs :	VGTs mass-produced and marketed since 2020
Improved-spec VGTs :	VGTs with improved reliability compared to current production-spec VGTs
Cost-saving-spec VGTs :	VGTs with reduced cost compared to improved-spec VGTs

2. Improvements for improved reliability

Turbochargers are devices in which a turbine wheel is driven by the engine exhaust gas and then a compressor wheel located on the same axis rotates to compress intake air and supply it to the engine.

VGTs have a drive mechanism that allows variable control of the nozzle area upstream of the turbine wheel. This variable nozzle makes it possible to control turbine characteristics according to engine speed and load. In addition, the nozzle can control the angle of gas flow into the turbine wheel, thereby improving supercharging efficiency.

The challenge in ensuring the reliability of VGTs for gasoline engines is dealing with high-temperature exhaust gases at temperatures exceeding 1,000°C. MHIET selected materials for the development of VGTs for gasoline engines, the temperature of which can exceed 1,000°C, considering the creep properties and wear resistance, and has additionally developed improved-spec VGTs with the following improvements regarding reliability.

2.1 Reduction of nozzle drive force by design improvement

The improved-spec VGTs require less driving force to open and close the nozzle vane as a result of revisions of each part design. The reduction of the required driving force is expected to reduce the frictional force acting on sliding parts and improve wear resistance. **Figure 1** shows examples of the part design revision. Figure 1 (i) shows the improvement of the linkage mechanism. The nozzle vane opens and closes with the driving force transmitted from the actuator installed in the VGT through the arm shown in Figure 1 (i), the drive ring, the vane lever, and to the nozzle vane. The improvement shown in Figure 1 (i) enhances the force transmission efficiency at the time when the vane is in the near fully open and near fully closed positions by revising the structure of the arm and drive ring. Figure 1(ii) shows the revision of the aerodynamic design of the turbine wheel and nozzle vanes. This revision optimized the fluid forces acting on the nozzle vanes. Figure 1(iii) shows the improvement of the scroll shape. Exhaust gas entering the VGT passes by the tongue and flows to each vane with swirling velocity component, and vanes immediately behind the tongue tend to be affected by the flow through the tongue and by the swirling recirculation flow, resulting in a large fluctuation in fluid force. In this example, the scroll shape was revised so that the recirculation flow acts predominantly on the vane immediately behind the tongue. These design revisions enabled the improved-spec VGT to reduce the driving force required to open and close the nozzle by up to 52%, improving wear resistance and also reducing opening hysteresis (variation in actual opening with respect to the same opening command depending on the operating direction). These improvements are expected to enhance the controllability in practical use and reduce wear on sliding parts.

2.2 Performance improvement

The effect of the aerodynamic design revision shown in Figure 1 (ii) contributes not only to the enhancement in wear resistance described above, but also to the improvement in the efficiency at the time when the vane is in the middle opening position, meeting recent requests from customers. Figure 4 shows the performance test results of the current production-spec VGT and the cost-saving-spec VGT. The cost-saving-spec VGT has improved peak efficiency by approximately 5% compared to the current production-spec VGT, which is expected to improve engine fuel efficiency.

2.3 Wear reduction by suppressing vane vibration

As shown in **Figure 2**, the improved-spec VGT has a connection path between the gas flow path and the linkage chamber, which has the effect of increasing the pressure in the linkage chamber and pushing the nozzle vane in one direction. This suppresses the vibration of the nozzle vane and is expected to reduce wear. By directly measuring the vibration of the nozzle vane during the engine operation, it was confirmed that the vibration was reduced to approximately 20% or less. In addition, in an engine durability test, it was confirmed that the amount of wear was reduced by 70% compared to the current production-spec VGT.

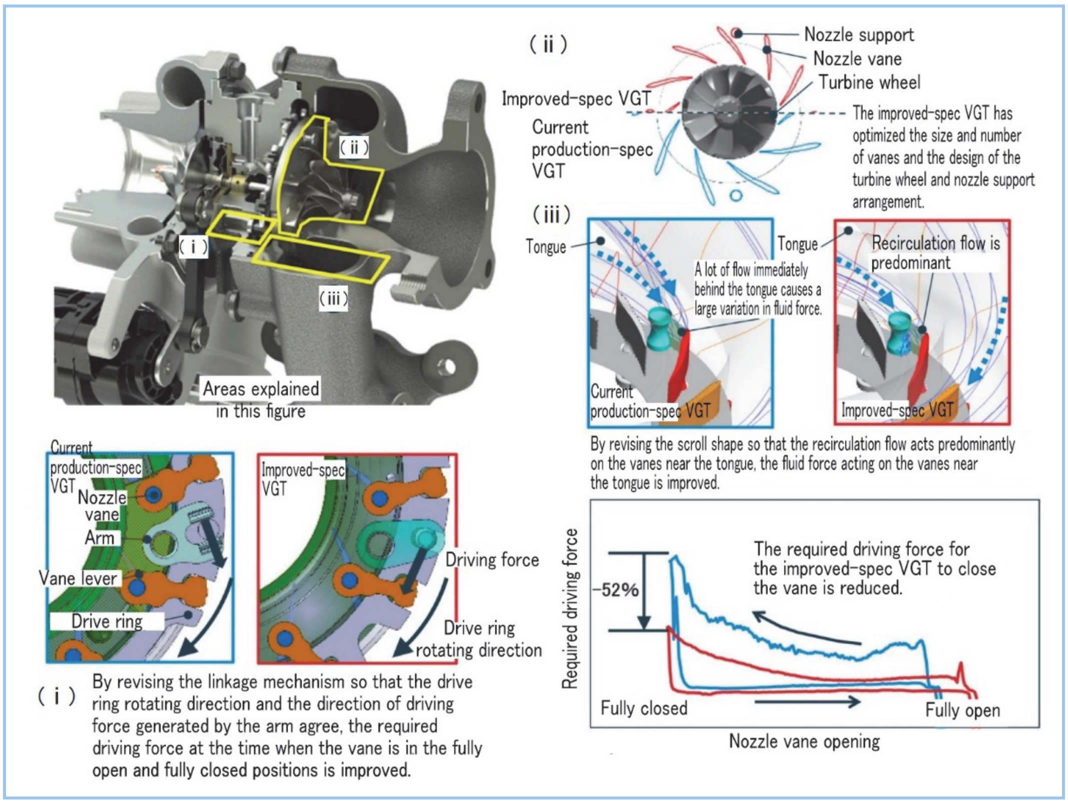

Figure 1 Reduction of nozzle driving force by design revision

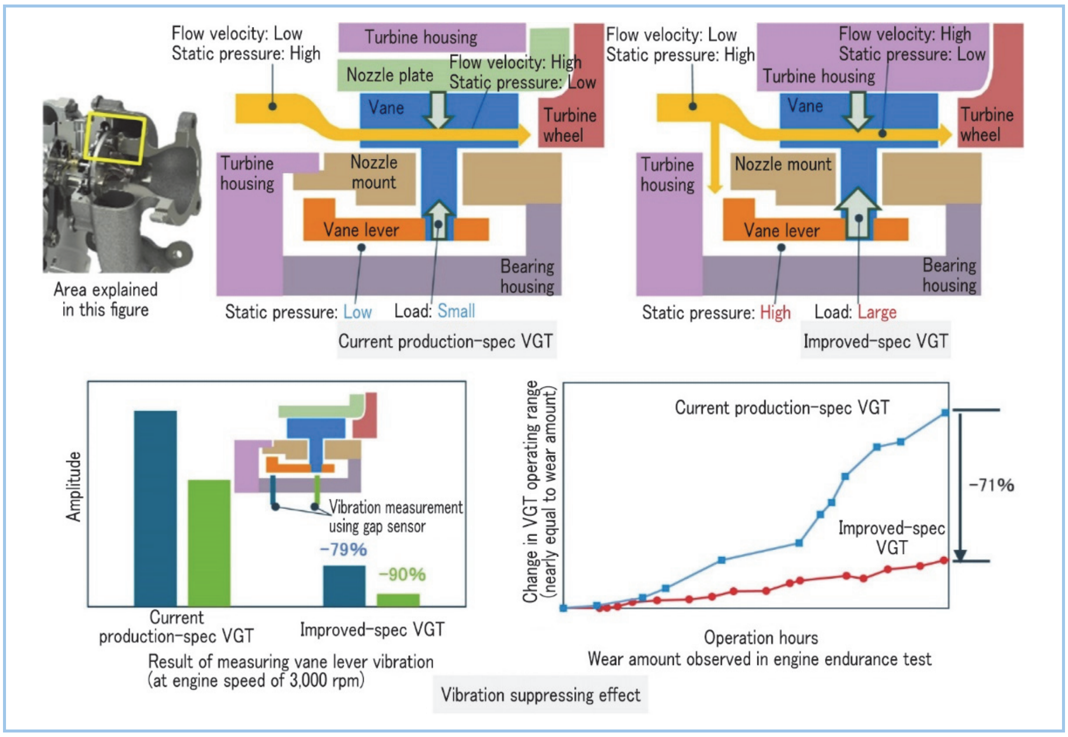

Figure 2 Vibration suppression by optimizing pressure balance around nozzle vane

3. Improvements for cost saving

VGTs for gasoline engines have a variable mechanism that can be exposed to exhaust gases at temperatures of around 1,000°C, making them more expensive than ordinary turbochargers that do not have the variable mechanism. On the other hand, customers' vehicle manufacturing costs have tended to increase due to the addition of hybrid systems, etc., and thus it is important to suppress the cost of engine manufacturing. Therefore, ensuring cost competitiveness is more important than ever for our VGTs to be adopted by our customers. Examples of MHIET's efforts to lower the cost of VGTs for gasoline engines are shown below.

Figure 3 shows the turbine side structure of the VGT for gasoline engines developed by MHIET. The upper half shows the cost-saving-spec VGT and the lower half shows the current production-spec VGT. The structural features of the cost-saving-spec VGT are the elimination of the nozzle plate and seal ring, and the reduction in the number of back plates.

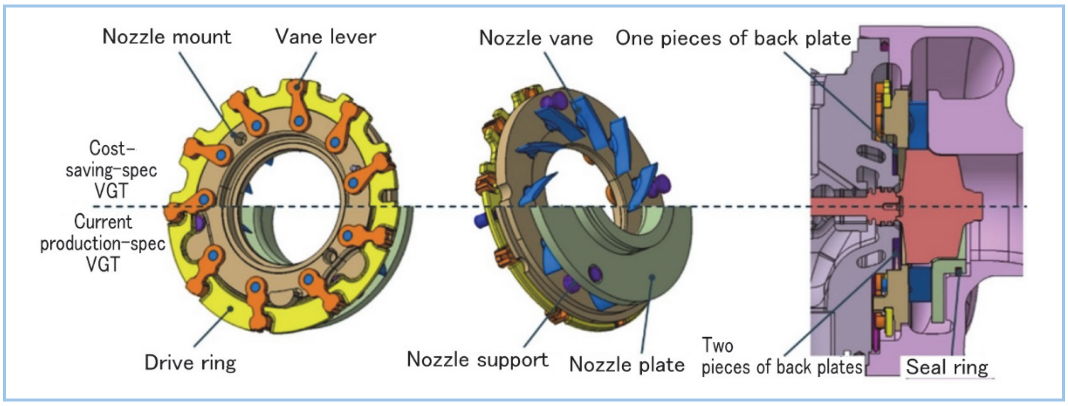

Figure 3 Structure of cost-saving-spec VGT

3.1 Reduction in number of parts by revising nozzle structure

By eliminating the nozzle plate, which also eliminates the need for the seal ring at the nozzle outlet, the cost-saving-spec VGT achieved a cost reduction due to the reduction in the number of parts. The functions previously performed by the nozzle plate and seal ring were taken over by the turbine housing. There was concern that this change could increase the thermal deformation of the plate and change the clearance around the vane, which would affect turbine performance. In designing the shape, we minimized the clearance change through FEM analysis. Consequently, the change in turbine peak efficiency before and after an engine durability test was within 1p as shown in **Figure 4**, confirming that the effect on engine performance is suppressed to a minimum.

The reliability improvements specific to the current production-spec VGT are described as follows. Conventionally, the nozzle plate was fixed to the nozzle mount through the nozzle support to define the nozzle vane sliding space. The nozzle plate and nozzle mount were thermally deformed by the exhaust gas during operation, but their thermal deformation behaviors were not identical, which could result in radial distortion in the nozzle support that fixed them together, causing a risk of breakage. On the other hand, the cost-saving-spec VGT eliminates the nozzle plate, and the turbine housing and nozzle support are in axial contact. However, they are not fixed in the radial direction, ensuring that the turbocharger can follow the thermal deformation during operation. This has improved the reliability of the turbocharger.

The cost-saving-spec VGT has a nozzle mount with a simplified shape, as shown in **Figure 5**. The nozzle mount of the current production-spec VGT has an integrally molded part that fixes the drive ring in the axial direction. Although this reduced the number of parts, the manufacturing method of the nozzle mount was limited and therefore, the cost reduction method was limited. The cost-saving-spec VGT expanded the options for manufacturing methods, materials, and heat treatment by simplifying the shape.

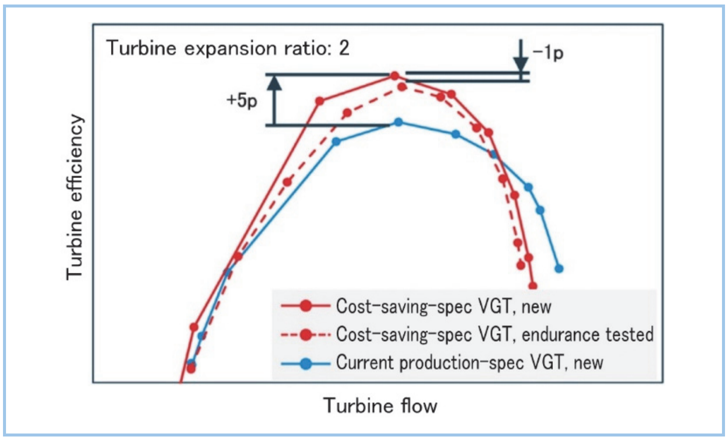

Figure 4 Performance test results of cost-saving-spec VGT

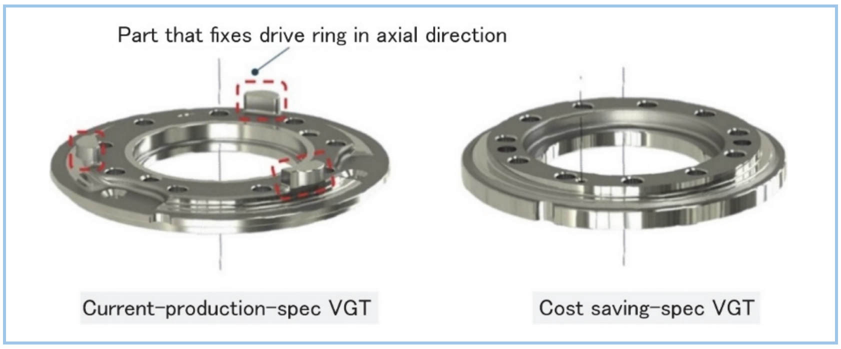

Figure 5 Comparison of nozzle mounts

3.2 Reduction in number of back plates by revising fastening structure

The current production-spec VGT has two back plates installed between the bearing housing and the nozzle mount. This layout is to absorb dimensional changes caused by thermal deformation during operation and to generate sufficient spring reaction force. The cost-saving-spec VGT successfully reduced the dimensional change of the back plate installation area by revising the fastening between the bearing housing and the turbine housing. This made it possible to obtain sufficient reaction force with only one back plate, thereby reducing the cost.

Figure 6 shows the VGT thermal deformation mode and the amount of deformation of the back plate insertion area. The thermal deformation of the back plate insertion part of the cost-saving-spec VGT is less than that of the current production-spec VGT. In addition, the thermal deformation of the cost-saving-spec VGT occurs in a direction toward the compression side of the back plate, which allows the high spring reaction force to be easily maintained even when thermal deformation occurs.

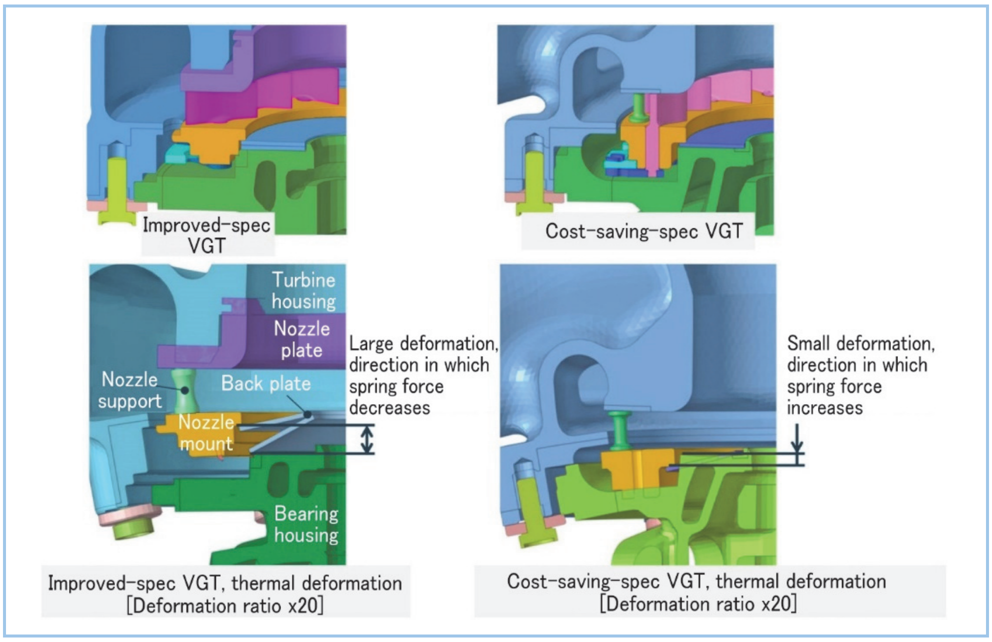

Figure 6 Deformation of back plate insertion area in thermal deformation

3.3 Revision of heat treatment

MHIET revised the heat treatments applied to nozzle components to reduce costs. Heat treatments applied to nozzle components are mainly conducted for wear resistance. Among the heat treatments applied to nozzles, the heat treatment applied to the nozzle mount was effective in terms of wear resistance, but the dimensional control thereafter was difficult, causing high costs. Therefore, the cost-saving-spec VGT eliminates heat treatment of the nozzle mount, and uses heat treatment for other parts the dimensions of which are relatively easy to control, thereby reducing costs while maintaining wear resistance. **Figure 7** shows the heat treatment applied to the nozzle components and the results of wear tests of the materials used in each part of the nozzle.

The "Low temperatures" in the figure refer to test results at metal temperatures of several hundred degrees Celsius, assuming idle operation, etc., and the "High temperatures" in the figure refer to test results at metal temperatures of each component where the exhaust gas temperature is around 1,000°C. In Figure 7, the wear of the drive ring material and the vane lever material in (i) was greatly reduced. The wear of the nozzle vane material and the nozzle mount material in (ii) and the nozzle mount material and the drive ring material in (iii) was maintained at the same level. By combining these results with the design changes shown in Section 2.3, both the wear reduction and cost reduction were achieved.

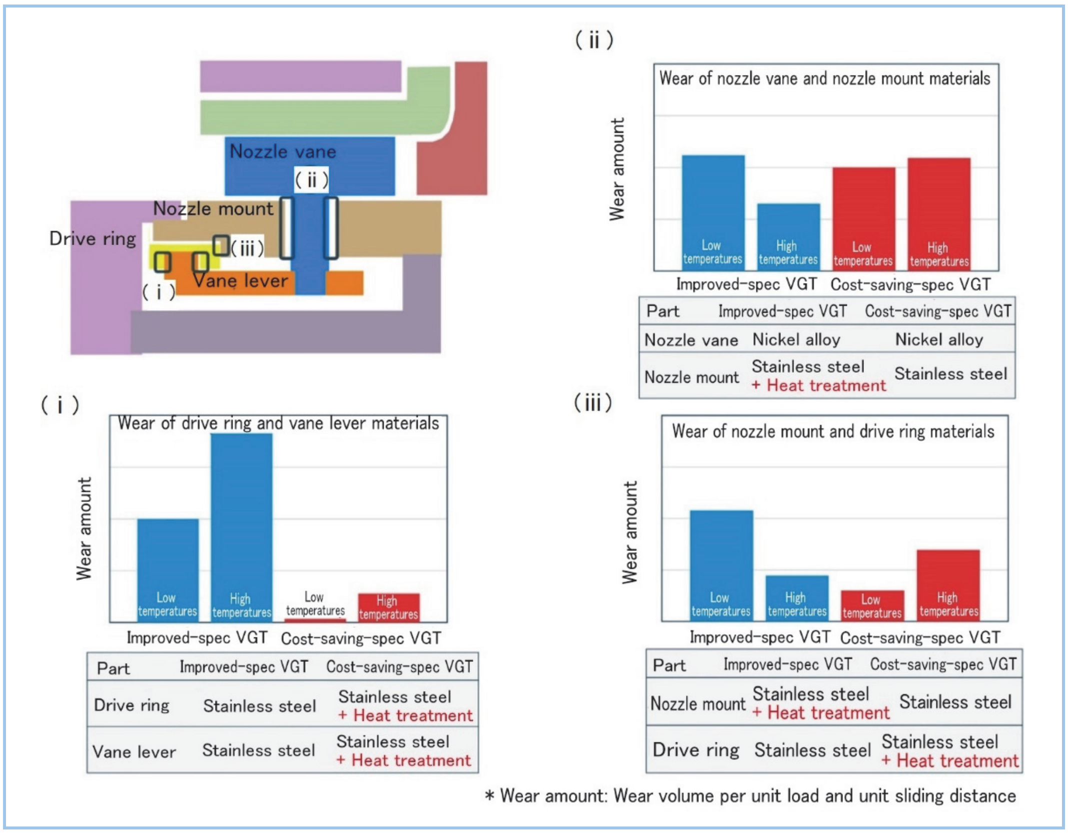

Figure 7 Materials of sliding parts and wear test results

3.4 Weight reduction by optimizing turbine housing wall thickness

Since the turbine housing of a turbocharger for gasoline engines contains a large amount of nickel to ensure heat resistance and accounts for about 30% of the manufacturing cost of the turbocharger, its weight reduction has a significant effect on reducing material costs. The turbine housing of VGTs can be made thinner than conventional ones because the nozzle section can provide part of the function of preventing debris ejection when the turbine wheel ruptures. The evolution of manufacturing technology has made it possible to mass-produce turbine housings by lost-wax casting (precision casting) instead of sand casting, which was the conventional manufacturing method. We have been working to reduce the weight of turbine housings by combining this with various optimization calculations of product geometry and manufacturing design.

Recently, the enhancement in the accuracy of FEM analysis and the improvement in casting design of turbine housings have made it possible to produce turbine housings by precision casting, which can reduce product tolerances resulting in weight reduction and less machining work.

Figure 8 compares turbine housings made by precision casting and conventional sand molding. MHIET achieved a 12% weight reduction by optimizing the shape and adopting precision casting for the turbine housing.

As a result of the above-mentioned efforts to reduce the cost of VGT, the turbocharger manufacturing cost was reduced by 15% compared with the current mass-production specification in the cost-down specification.

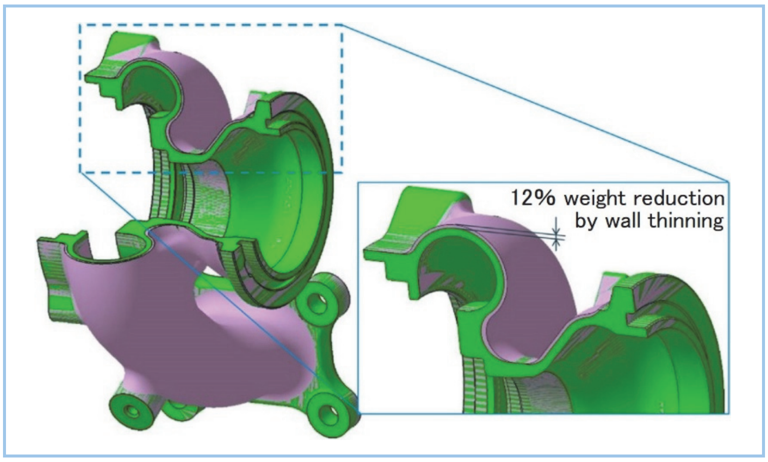

Figure 8 Effect of turbine housing made by precision casting

4. Dealing with short-term development through utilization of systems engineering

Systems engineering is a development method conventionally used in the aerospace, defense, and aircraft industries, but recently, it has also been utilized in the automotive industry. Systems engineering uses an approach called the V-shaped process. In the process, customer requirements are incorporated into specifications in the order of systems, subsystems, and components, and their verification is performed and built up in the reverse order, starting with the smallest unit. The V-shaped process can create products and systems that are steadily based on requirements, and is an effective method for preventing rework.

Figure 9 shows examples of the application of systems engineering at MHIET. In our systems engineering for the development of turbochargers, the requirements from the customer are clarified as engineering requirements for the turbocharger. The clarified engineering requirements are assigned as functional target values to the turbocharger's composing subsystems, such as the compressor, bearings, and turbine, as well as to each of the parts that compose the subsystems. By verifying by system that each part/system satisfies the assigned functional target values and by confirming the validity between system levels, it is ensured that the customer's requirements can be met. MHIET has established a process to consolidate in a database the design basis for turbocharger specifications responding to customer requirements and information on verification tests, and then utilize this database for design work. Using this process to make it easier to respond to requests from customers to submit the design basis, etc., we are working to gain trust from customers and win orders.

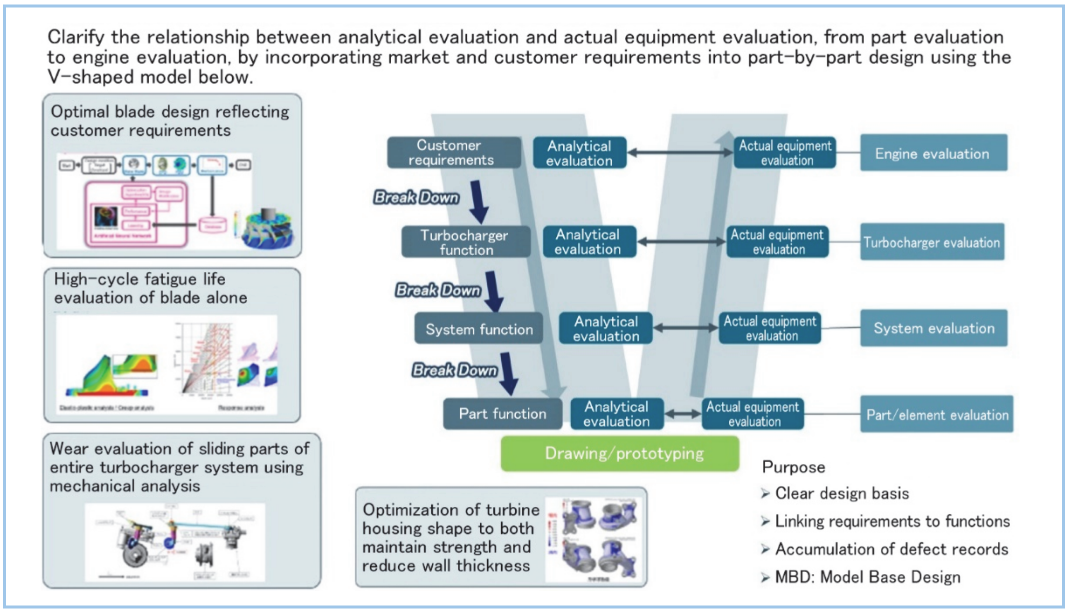

Figure 9 Utilization of systems engineering in turbocharger development

MHIET has compiled a database of verification methods and results built up in product development, visualized them, and utilized them in product design. The results reported in this paper have expanded the database. In the future, we will utilize this database for the development of new models and short-term development with customers.

5. Conclusion

MHIET worked on structural improvements of VGT to enhance its reliability and achieved wear reduction and controllability improvement.

We will continue our approach to obtain orders for VGTs from the North American market by utilizing the results of these efforts.

References

(1) Y. Danmoto et al., Development of VG Turbocharger for Next-Generation Gasoline Engines, Mitsubishi Heavy Industries Technical Review Vol.56 No.2 (2019)

(2) K. Sakaguchi et al., Development of Turbocharger Dedicated to Series-hybrid Engines, Mitsubishi Heavy Industries Technical Review Vol.60 No.2 (2023)