

# Development of Compact and High-performance Turbocharger for 1,050°C Exhaust Gas

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The control of global exhaust gas emissions and the legislation concerning fuel consumption have promoted the reduction of the size of engines for passenger automobiles, and as a result, the engine output per unit cylinder displacement is increasing. As the turbocharger is an effective way of making high-output engines smaller, the demand for turbochargers is increasing, and technological improvements are required. The exhaust gas temperature of gasoline engines is rising, giving better combustion efficiency, and this requires the timely development of compatible turbochargers. In the face of this global demand, Mitsubishi Heavy Industries, Ltd. (MHI) has developed, and has started delivering to customers, compact and high-performance turbochargers capable of operating at 1,050°C, the world's highest level of exhaust gas temperature.

## 1. Introduction

To cope with present environmental restrictions, small displacement engines equipped with a turbocharger are increasingly used in place of naturally aspirated large-displacement engines, while maintaining a similar level of engine output. This so-called “downsizing” trend helps to increase the number of turbochargers required. In the past, turbochargers for gasoline engines were only used on a few models of high-performance sports cars produced in small quantities for a limited number of customers. However, the recent wave of downsizing has prompted turbochargers to be installed on an increasing number of gasoline engines.

The sharp increases in the price of gasoline and the strict control of CO<sub>2</sub> emissions (see Fig. 1) are the reasons behind the strong drive for better fuel consumption.<sup>1</sup>

With the demand for gasoline engine turbochargers is expected to increase, and engine operating conditions are expected to become more severe (e.g., increased exhaust gas temperatures), a turbocharger capable of dealing with high exhaust temperatures is urgently required.

## 2. Features of turbochargers for gasoline engines

The exhaust gas temperature of a gasoline engine is generally about 200°C higher than that of a diesel engine, and thus requires a more sophisticated turbocharger that can withstand the higher temperature. Exhaust gas temperatures are further increasing to cope with recent emissions restrictions and the demand for small but powerful engines. The requirement to handle exhaust gas temperatures as high as 1,050°C has already been identified (see Fig. 2).

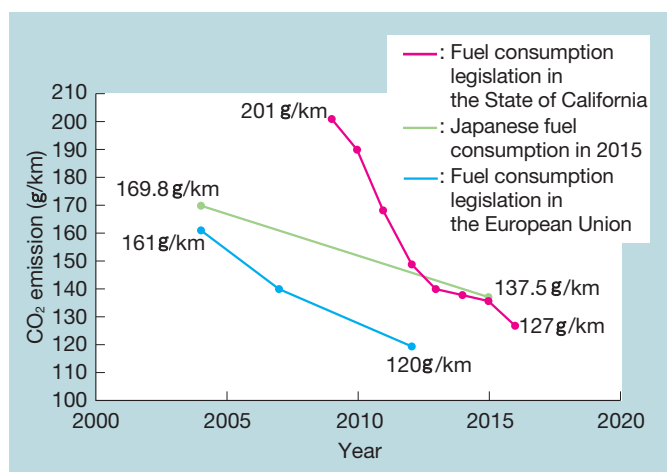


Fig. 1 Transition of CO<sub>2</sub> emission levels regulated by areas

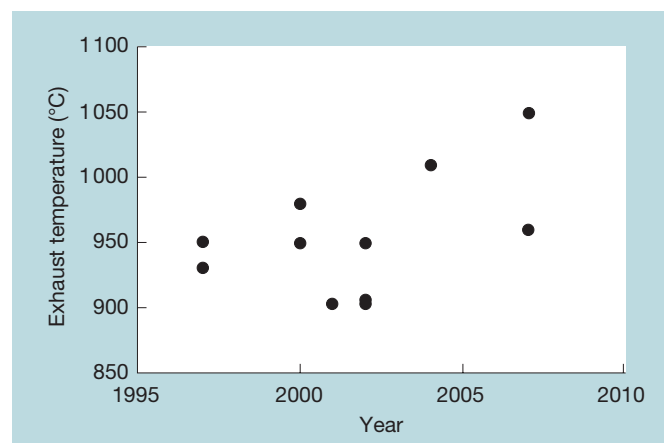


Fig. 2 Transition of gasoline engine exhaust gas temperature for MHI's customers

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In a fuel-injected engine where fuel is injected into the intake port, it is general practice to set the engine compression ratio lower than that of a naturally aspirated engine in order to avoid knocking. However, due to the cooling effect of the vaporization heat of the fuel spray that suppresses knocking, the direct-injection engine can maintain a compression ratio comparable to that of the naturally aspirated engine. However, this raises the turbine inlet pressure and increases the load on the turbocharger.<sup>2</sup>

While the demand for gasoline engine turbochargers is increasing, the functional requirements such as high exhaust gas temperature and pressure require urgent development of a durable turbocharger. The following functions must be evaluated to verify the durability requirements.

- Strength of the turbine wheel
- Strength of the turbine housing
- Optimization of the wastegate valve mechanism

The next section discusses these factors in detail.

### 3. Technologies to cope with high exhaust temperaturea

#### 3.1 Turbine wheel

Inconel is a standard material for turbine wheels. This nickel-based heat-resistant alloy, however, does not meet MHI's criteria for anti-creep characteristics at 1,050°C, MHI has decided, therefore, to use MarM, a similar nickel-based heat-resistant alloy with greater strength at high temperature. While MHI has used MarM for the turbochargers in competition vehicles such as rally cars, this is the first time that MHI has used MarM in mass-produced vehicles. Since MarM is more difficult to cast and more likely to have minute casting defects than Inconel, MHI uses hot isostatic pressing (HIP) on MarM to remove casting defects and to homogenize the material structure. HIP is a metal treatment technology that uses an inert gas such as argon as a pressurizing medium and utilizes the synergistic effect of a pressure normally greater than 100 MPa and a temperature higher than 1,000°C.

Before using MarM in mass-produced vehicles, MHI

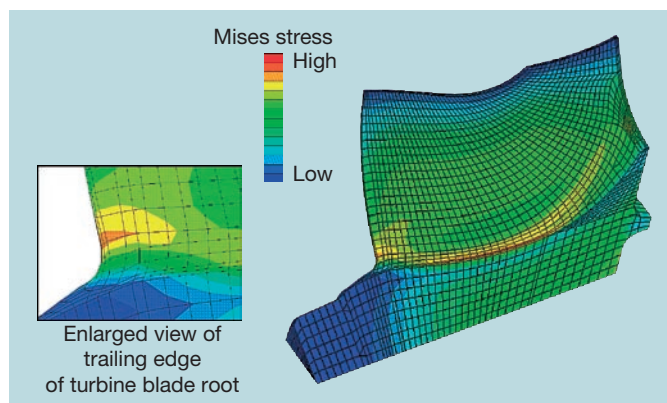


Fig. 3 Turbine wheel stress analysis (Mises stress)

subjected it to a high-temperature tensile test and a creep rupture test to supplement the material characteristics data before conducting turbine wheel stress analysis (see Fig. 3) and creep analysis. Since estimation of the actual turbine blade temperature is critical to the creep life evaluation, an infrared thermometer was used to measure the blade temperatures of the rotating turbine wheel. An over-speed burst test and a creep rupture test were conducted on an actual turbine wheel to verify its reliability. Figure 4 shows photographs of the turbine wheel after the creep rupture test at an exhaust gas temperature of 1,050°C and the highest rotational speed. The figure shows a creep rupture starting at the root of the blade at the trailing edge of the turbine, which is a high stress location determined by previous analyses. Furthermore, comparison test with the conventional Inconel turbine wheel showed that the creep life of the MarM turbine wheel is about three times as long.

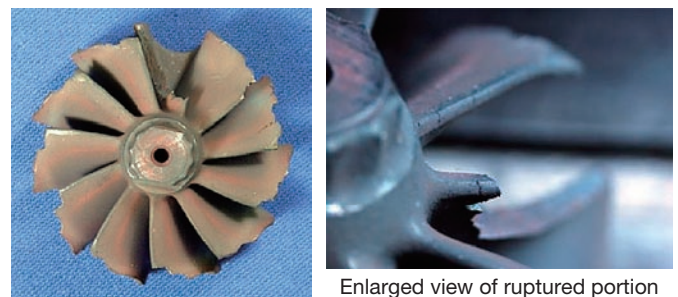


Fig. 4 Turbine wheel creep rupture test at an exhaust gas temperature of 1,050°C and maximum rotational speed

#### 3.2 Turbine housing

MHI has an array of turbine housing materials to meet customer exhaust gas temperature requirements, including ductile cast iron with an allowable temperature of 700°C and austenitic stainless cast steel that resists temperatures exceeding 1,000°C (see Fig. 5). Many turbine housings

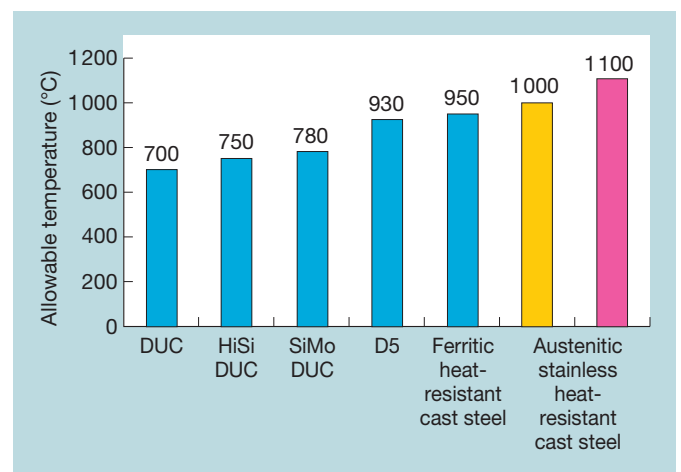
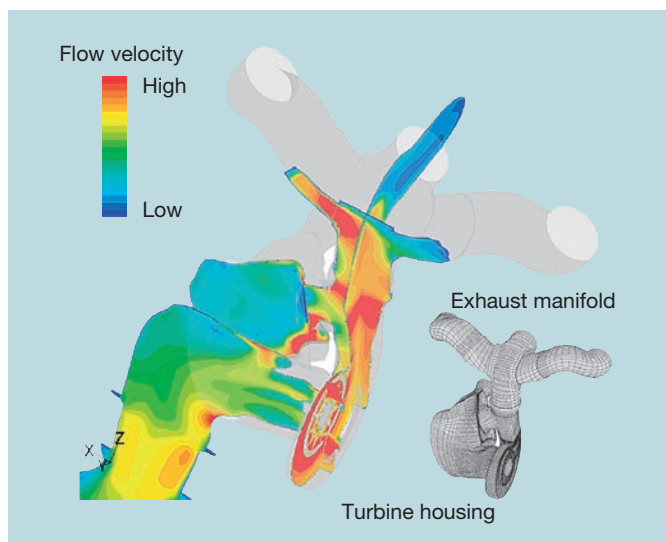
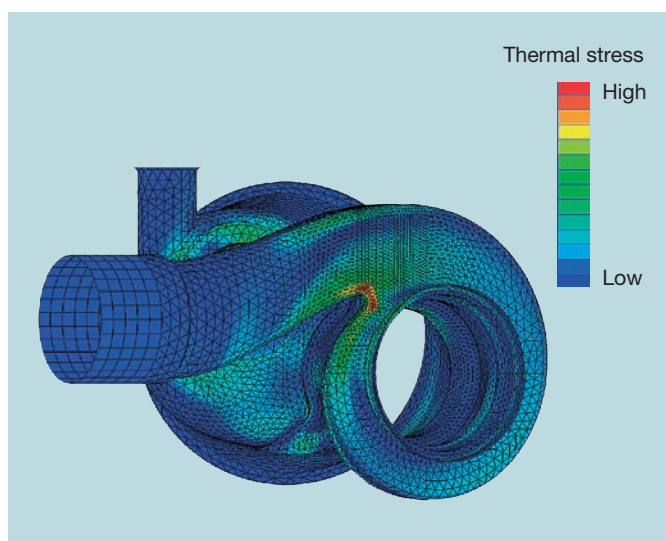


Fig. 5 Turbine housing materials and allowable temperatures

of recent gasoline engine turbochargers are made of austenitic stainless cast steel. Optimization of turbine housing profiles is as important as material selection in ensuring the strength at elevated temperatures. The engine operating conditions expose the turbine housings to repeated heating and cooling, making them subject to possible cracking through thermal fatigue. To avoid thermal cracks, MHI conducted an exhaust gas flow analysis (see **Fig. 6**), a heat transfer analysis between the exhaust gas and the turbine housing, and a turbine housing thermal stress analysis, all under transient operating conditions, corresponding to the engine operating conditions, to locate the high-stress regions (see **Fig. 7**). In addition to using austenitic stainless cast steel, eliminating the structural discontinuity from the turbine housing and the use of a more uniform wall thickness helps to prevent the generation of cracks.



**Fig. 6 Results of flow analysis (flow velocity distribution)**



**Fig. 7 Example of thermal stress analysis of turbine housing**

### 3.3 Wastegate valve

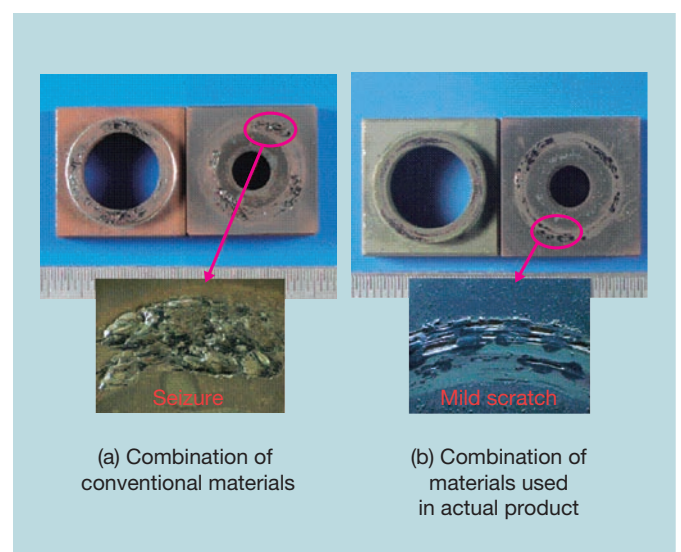
The wastegate valve bypasses exhaust gas to control the air pressure entering the engine. Since the wastegate valve must operate without lubrication while being exposed to an exhaust gas of higher temperature, its resistance to seizure is particularly important.

MHI's development included a high-temperature wear test of the wastegate valve material on the test bench shown in **Fig. 8** to verify its anti-seizure characteristics. The results suggested a combination of materials with anti-seizure characteristics that exceed those of conventional materials (see **Fig. 9**).

In addition, a structural analysis was conducted to optimize the wastegate valve mechanism to reduce the

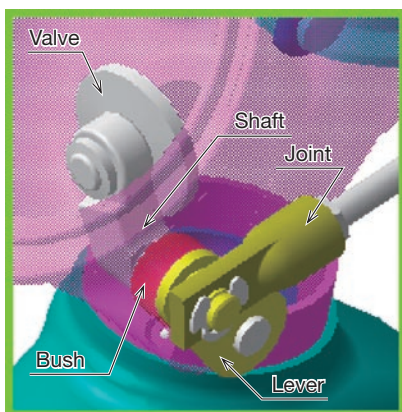


**Fig. 8 High-temperature wear test bench**



**Fig. 9 State of sliding surfaces after high-temperature wear tests**

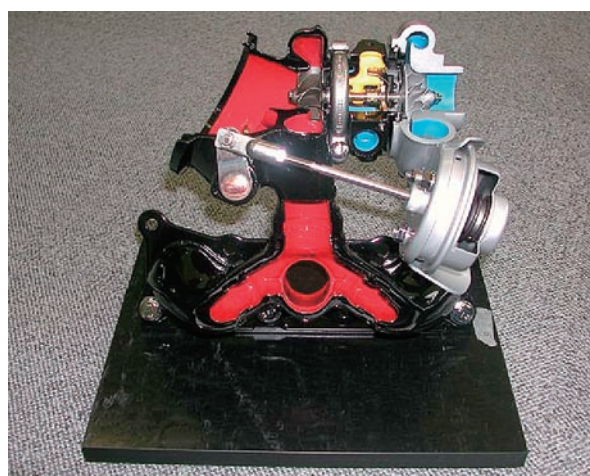




**Fig. 10 Wastegate valve structural analysis model**



**Fig. 12 Turbocharger with unitized exhaust manifold (unitized casting)**



**Fig. 13 Turbocharger with unitized exhaust manifold (weld-fabricated structure)**

wear. **Figure 10** shows the structural analysis model. Using the dimensions of each member of the mechanism as parameters, the simulation took place while applying variable loads equivalent to the exhaust pulsation to evaluate the severity (slide amount and load) of the sliding section. **Figure 11** shows an example of the calculated results. This analysis provided MHI with dimensions that reduced the severity of the wear, and this design was incorporated into the end products.

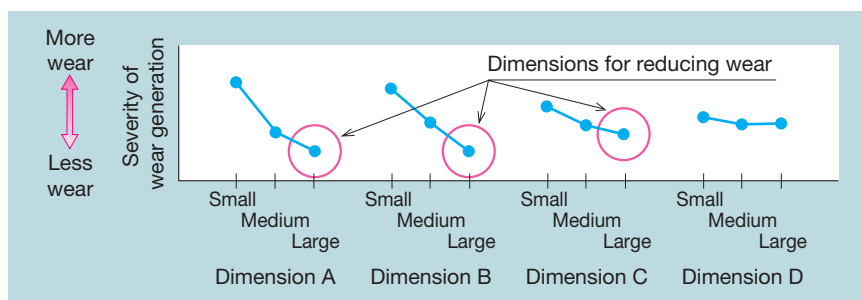
#### 4. More compact and higher performance

To design a simple engine compartment layout, a compact turbocharger design is required. The demand for compact turbochargers is increasing because of the requirement to shorten the catalytic activation time at engine startup and to reduce the thermal capacity of the exhaust gas passage that reaches the catalyst. Since the catalyst must be hot to be active, it is necessary to reduce the amount of heat absorbed by components on the exhaust gas passage such as the exhaust manifold and turbine housing. To meet this requirement, MHI has been delivering turbochargers in which the exhaust manifold and turbine housing are combined in a single cast part (see **Fig. 12**). To make the turbocharger even more compact and lightweight, MHI has developed a production method, jointly with a customer, whereby the exhaust manifold is press-formed from a sheet of stainless steel and welded to the cast turbine housing (see

**Fig. 13**). The exhaust manifold is double-walled, and this greatly reduces its thermal capacity.

#### 5. Conclusion

To meet the requirements of the increasingly stringent legislation on exhaust emission and fuel consumption, MHI has concentrated its efforts on high-temperature exhaust gas turbochargers for gasoline engines. MHI has



**Fig. 11 Example of calculation of wear severity by structural analysis**

successfully developed, and has started to deliver, compact high-performance turbochargers capable of dealing with an exhaust gas temperature of 1,050°C, the highest in the world. By conducting further thermal stress analysis and structural analysis of sliding mechanisms to evaluate design before prototyping, MHI is meeting exacting customer needs and reducing development time to deliver better automobile environmental performance and driving pleasure.

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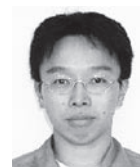
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