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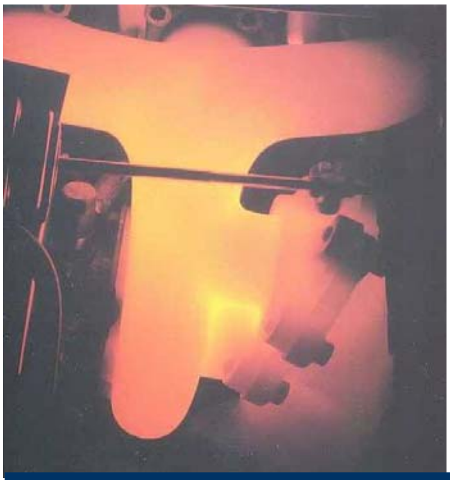

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Exhaust gas temperature 1050° C

An engineering challenge

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Academy

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Introduction

The European Automobile Manufacturers Association EAMA has made an obligation to reduce the average carbon dioxide emissions in new vehicles to 140 g/km by the year 2008. This corresponds to a fuel consumption of 6.0 l/100 km for gasoline passenger cars and of 5.3 l/100 km for diesel passenger cars /1/. Furthermore, examinations are currently being performed to see if an EU threshold of 120 g/km is achievable by the year 2012. Even lower CO_2 emission levels of 90 g/km are being discussed for the year 2010 by the EU in accordance with the goals of the Kyoto Accord.

If you assume an average CO_2 emission value of about 190 g/km in Europe, then you can see which technical developments are necessary to achieve these high goals. An increase in the percentage of diesel passenger cars in the fleet of passenger cars in Europe definitely has a positive effect on the CO_2 emissions, but this alone will not lead us to the goal. Emphasis must be placed in development on improving the most commonly used drive unit, the gasoline engine, with respect to its efficiency and emissions. Considering the fact that 75% of all vehicles in Europe are driven by gasoline engines, the greatest effect would be gained by improving this engine design.

One of the most promising measures to reduce fuel consumption is downsizing. In this concept, large displacement, naturally aspirated engines are replaced by supercharged engines with small displacements and fewer cylinders. Downsizing leads to a shift in the load points of the engine operating points into areas of higher efficiency. Smaller, more compact engines with fewer cylinders also have lower losses due to friction and are lighter than naturally aspirated engines with the same performance. Reductions in consumption of up to 20% can be achieved through consistent downsizing /2,3/. Currently, engines with 3 or 4 cylinders and cylinder capacities between 0.6 and 2.0 liters are being discussed. The output density can vary between 60 kW/l and 100 kW/l /4,5/.

The newest generation of charging systems from BorgWarner Turbo Systems will therefore need to fulfill even higher demands than has been the case so far.

- In future gasoline engines the demand for charging pressure will increase and the air flow rate range will expand. The startup torque of the small displacement engine can be improved through the use of variable turbines (VTG or VST), eBoosters or multistage charging systems /6/.

- The exhaust temperatures of future turbocharged gasoline engines will increase. The air ratio at the rated output point is currently about λ=0.75-0.85 since a portion of the fuel is used to cool the inside of the engine. If the air ratio is increased to a value between λ=0.9-1.0, then a potential fuel savings of up to 20% can be attained. The exhaust temperature will rise by about 50 to 100 K depending on the air ratio /3/.

- The thermal inertia and the surface area of the turbine housing are to be kept as small as possible to keep emissions low. A reduction in the weight in this context also benefits the total weight of the vehicle.

Current state of the art

The structural design of the exhaust side of a turbocharger generally consists of a turbine housing and the turbine wheel. The turbine converts the energy of the exhaust gas from the engine to mechanical energy to drive the compressor and to overcome the bearing losses. The turbines used in passenger cars are called radial-flow turbines or centripetal turbines. Modern passenger car gasoline engines already place the highest possible demands on the thermal load capacity of exhaust turbochargers. The maximum permissible temperature on the turbine inlet under steady-state engine conditions is currently about 970°C. Higher temperatures can arise for short periods of time, though.

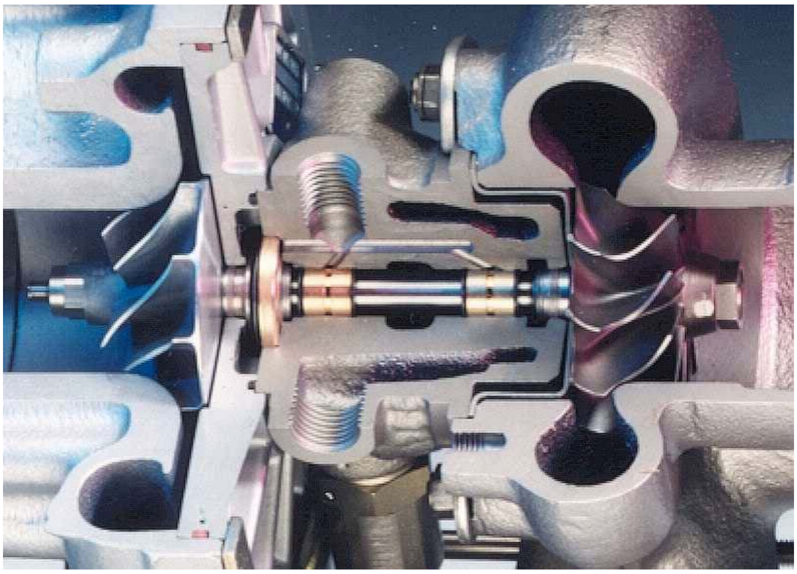

Figure 1: Cross-section of the bearing housing of a K16 turbocharger

Four different media flow through extremely close quarters in a turbocharger designed for gasoline engines: hot exhaust, air (which should stay as cold as possible), oil (which cannot be allowed to become too hot) and water (in which no steam bubbles should form). A rotor in the turbocharger rotates at a speed of 160,000 to 300,000 rotations per minute depending on its size. A temperature gradient of about 800°C reigns over a distance of a few centimeters in the rotor itself during operation.

Components with high thermal loads include the bypass valve, the turbine wheel and the heat shield (which prevents heat from penetrating the bearing housing), in addition to the turbine housing itself. The shaft and piston ring and the mounting bolts with clamping segments are also subject to a high thermal load. The bearing housing is generally water-cooled for applications on gasoline engines to prevent inadmissible increases in temperature on the piston ring on the turbine side and in the bearings during operation and, in particular, after the engine has been turned off /7/.

The turbine housing is therefore of primary importance since it is subject to a high thermal load and is also the most expensive component due to its size, complexity and materials. The comparatively thin walls of the housing, the complex and sometimes delicate structure with high temperature gradients within the component as well as the constantly changing temperatures during operation are already engineering challenges, especially when the turbine housing possesses an integrated exhaust manifold as shown in Figure 2. From Figure 2 you can see that the turbine is subject to a higher load than the exhaust manifold. This is a result of combining all exhaust pipes of the manifold before the turbine.

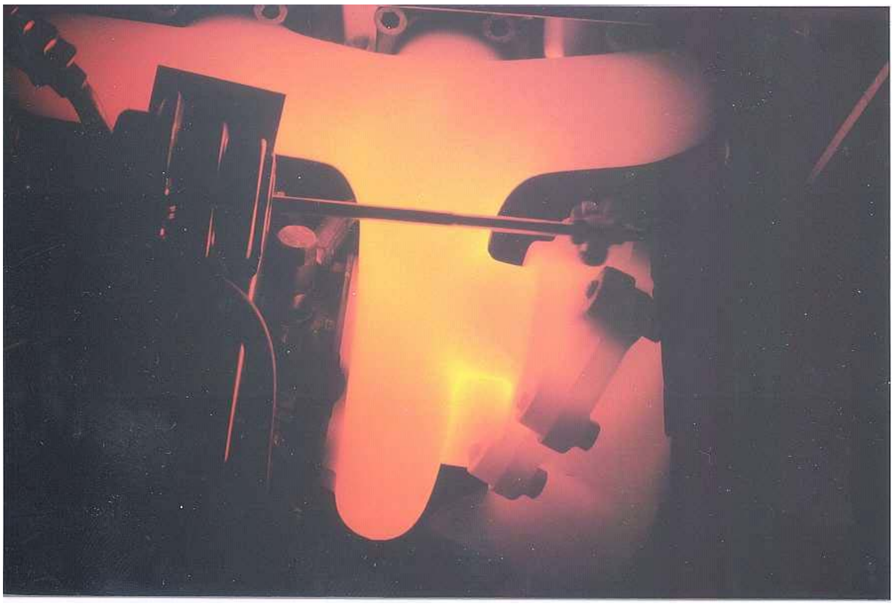

Figure 2: K16 turbocharger for gasoline engines with integrated exhaust manifold operating at full capacity

This engineering challenge can only be met in an era where product cycles are becoming shorter and shorter. This era is only possible due to the application of years of experience and the use of the most modern engineering and simulation methods. Figure 3 contains a diagram of the temperature distribution inside the turbine obtained through 3D flow calculations (as a representation of the results of a simulation).

In the example shown, a gas temperature of 950°C is encountered at the gas inlet. At this steady-state operating point, the inner wall of the turbine housing near the inlet flange, parts of the volute and the area behind the open bypass valve become as hot as the temperature of the gas at the inlet. The temperature gradient on the inside of the turbine housing is about 100°C at this operating point. Beyond this operating point, experience has shown and calculations have confirmed that the temperature gradient drops to about 80°C due to heat dissipating into the environment.

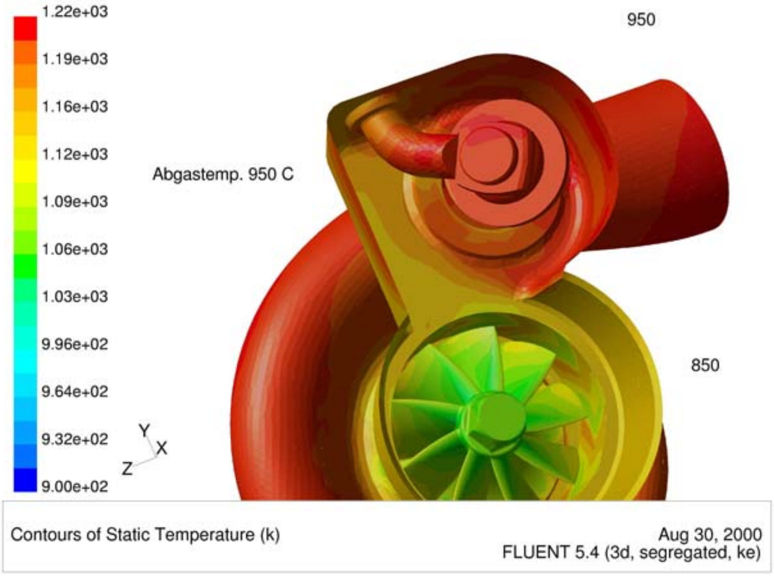

Figure 3: Model calculation of the temperature distribution in the turbine

Nowadays, turbine housings are usually made of GGG NiCrSi 35 5 2 (also referred to as Niresist D5S) manufactured using the sand casting method. The reference literature indicates a maximum application temperature of 850°C, in special cases of up to 900°C, for austenitic cast iron with spheroidal graphite /8/. In practice, the service life of the turbine housing is calculated based on load spectra. A deciding parameter in this regard is the percentage of time at full capacity at exhaust temperatures over 900°C. The load spectra used today generally assume this is the case 5% of the time.

When future downsized engines appear, it can be assumed that the percentage of time operating at full capacity and the heat generation rate will increase due to the small size of the basic engine. This must be taken into account when calculating the service lives of future turbochargers. This fact and the general increase in exhaust gas temperatures up to 1050°C, a temperature encountered in modern engine designs, require almost the complete redesign of the turbocharger and the use of higher quality materials. This also includes the refinement of existing turbines with variable geometries for gasoline engines.

Turbochargers for an exhaust temperature of 1050°C

Turbine housing

The cast steel turbine housing

Turbochargers for exhaust temperatures of 1050°C require a material for the turbine housing that will withstand such high component temperatures during the entire service life of the vehicle. Heat-resistant cast steel is ideal for this purpose. Turbine housings made of heat-resistant cast steel are already being used today by BorgWarner Turbo Systems for mass-production customer engines /9/.

Heat-resistant cast steel is certainly a commonly used material in plant engineering and construction, for example in the petrochemicals industry and in the steelmaking industry. In comparison to the delicate turbine housings for passenger car turbochargers, these workpieces are relatively large and have substantially thicker walls. Typical requirements from the automobile industry, such as the demand for small components with complex structures while simultaneously demanding a great number of components at comparatively low prices, are currently only met in part due to low demand.

There are two types of cast steel, the ferritic and austenitic cast steel types, whose properties differ significantly. The advantages of ferritic types of cast steel are the low alloying costs, low thermal expansion and good casting properties. The ferritic types have a reduced creep strength over time for the same temperature when compared to the austenitic types. They are more brittle due to their carbide content and are only somewhat resistant to cyclic thermal stress. The austenitic cast steel types have a higher creep strength, good resistance to cyclic thermal stress, are easy to cast and are usually easy to weld /10,11/.

For this reason, only heat-resistant austenitic cast steel types with a high nickel and chromium content will be used for applications at 1050°C by BorgWarner Turbo Systems. The long-term creep strength is an important parameter when evaluating the material used to make a turbine housing. Figure 4 plots the creep behavior after 10,000 hours against the temperature for the material Niresist D5S in comparison to other types of cast steel. The great potential and attractiveness of the heat-resistant cast steel can easily be recognized.

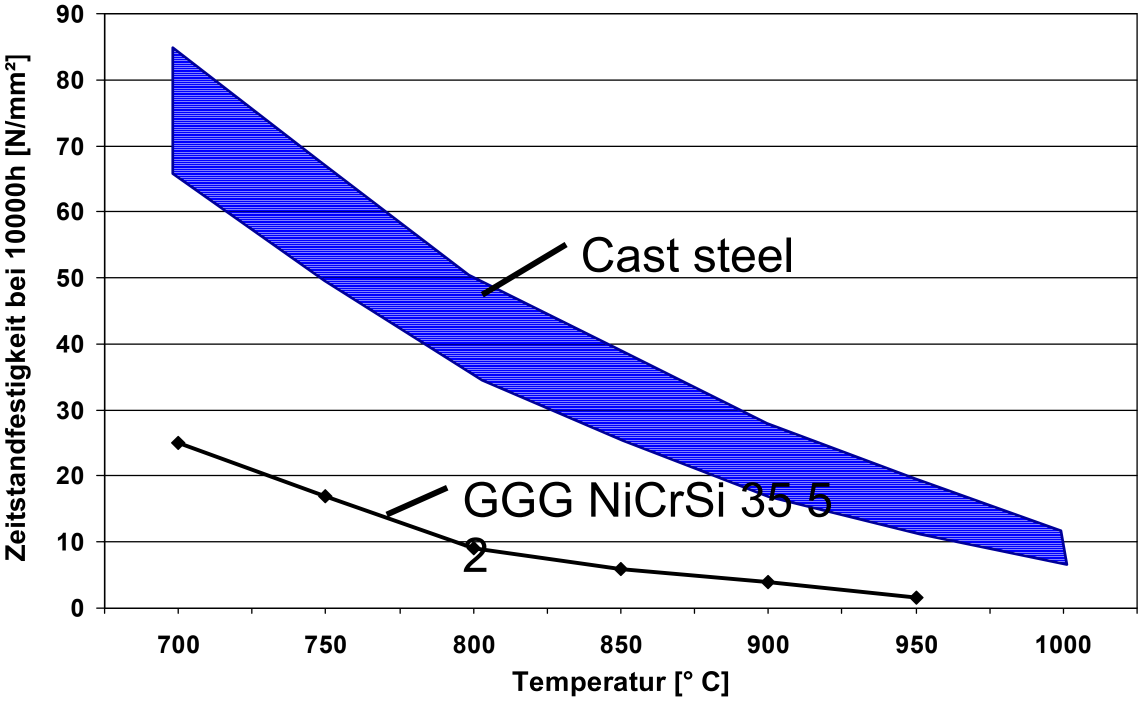

Figure 4: 10,000 h creep strength of turbine housing materials for gasoline engines

However, these advantages come with some disadvantages in terms of their manufacturing that lead to higher costs. On the one hand, cast steel as a material is much more difficult to cast than Niresist D5S. The higher casting temperature (about 200 – 300°C higher) of the cast steel and the higher density require fireproof and extremely stable outer shells and cores. High-purity quartz sand and high quality binding agents are used for this purpose. The design of the feeder head and riser system, which must be removed from the raw cast part in a time/cost-intensive procedure, is substantially more complex. It is not possible to use Niresist D5S casting equipment for casting steel.

On the other hand, it is much more difficult to machine heat-resistant cast steel due to its high viscosity and the strength of the material. The high cutting forces required to obtain optimal machining results can only be applied in part because the turbine housing can become deformed when the cutting forces are too high. It is especially difficult to drill holes and cut threads because the large contact surfaces cause the material being cut to stick to the cutting tool in this case. The machining times are therefore longer and the wear on the tools is higher.

The thin-walled turbine housing

The complexity of the manufacturing and machining processes for turbine housings made of cast steel and the high costs arising in connection with them has raised the question of what benefits the customer derives from these technologies. Thin walls are desired to significantly reduce the weight of the turbine housing and simultaneously reduce the thermal inertia of the turbine housing. This leads to faster activation of the catalytic converter during the cold-start phase of the engine, which in turn significantly improves the emission levels of the vehicle.

The stamped steel turbine housing

From the variety of possible alternatives examined, the stamped steel turbine housing represents the most interesting solution. It consists of several stamped steel parts that are welded together. The turbine housing can have a single-flow or double-flow construction with air-gap isolation.

Figure 5: Turbocharger with stamped steel turbine housing

The turbine housing can be connected to the neighboring pipes of the exhaust system of the engine by a flange or by welding it to the pipes. As a result of this, it is possible to have continuous air-gap isolation for the flow of exhaust from the cylinder head all the way down to the catalytic converter. Heat resistant sheet steel is available as a material that permits exhaust temperatures of up to 1050°C. Tests run on the turbocharger test bench have confirmed the low thermal inertia. Stamped steel turbine housings are just as good as cast turbine housings in terms of their efficiency and flow characteristics.

The precision cast turbine housing

Another interesting alternative is the precision cast turbine housing, which can be made of any castable material. Through manufacture using the precision casting process, the thickness of the walls of the turbine housing can be reduced by more than 50%. Results just as good as those for stamped steel turbine housings are achieved in terms of thermal inertia and weight savings with this turbine housing.

The advantage over stamped steel turbine housings is the ease of integration of the bypass valve in the housing and the lower tool costs expected when compared to a stamped solution made of sheet steel. Precision cast turbine housing can generally be manufactured from all austenitic types of cast steel and are generally suitable for an exhaust gas temperature of 1050°C.

Figure 6: Cross-section of a precision cast turbine housing

Turbine wheel and shaft

The turbine wheel is the component of the turbocharger subject to the highest load because of its high mechanical load in addition to the high temperature. The increase in the exhaust gas temperature for gasoline engines from its current value of ~950°C to 1050°C means that even higher quality materials need to be used for the turbine housing and turbine wheel since the Inconel 713C currently used does not exhibit sufficient thermal stability. This type of material must have a minimum of the same creep strength at significantly higher temperatures. The value of the temperature and the temperature distribution on the wheel were determined with the help of numerical simulations like the one shown in Figure 7 for an exhaust gas temperature of 1050°C.

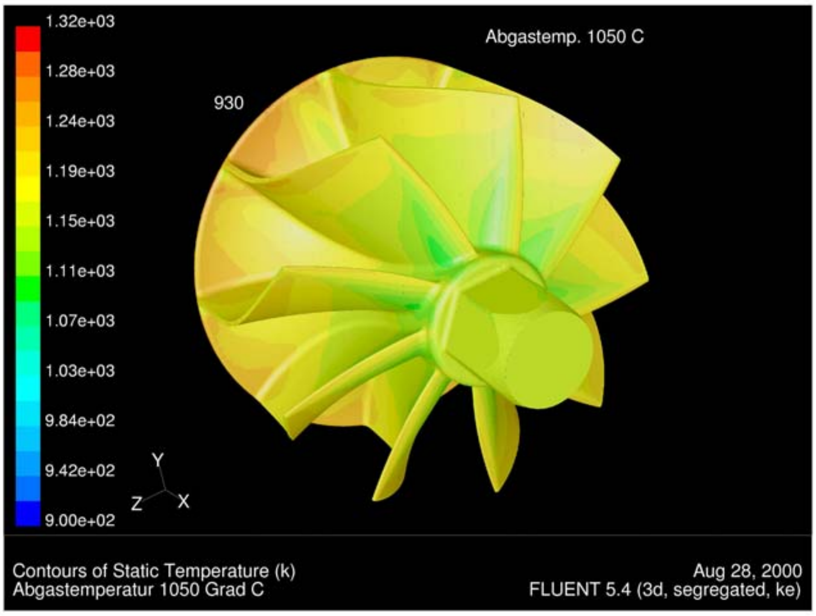

Figure 7: Temperature distribution on the turbine wheel at an exhaust temperature of 1050°C

Turbine wheel thermodynamics are not to be compromised by the use of the new material. The current geometry of the turbine wheel should be able to be manufactured using a casting process. The manufacturing process of the turbine wheel should not change either for reasons of cost. Turbine wheels are manufactured using a highly creep-resistant nickel-based alloy that is melted and cast in a vacuum. The use of ceramic turbine wheels, which have been highly refined at BorgWarner Turbo Systems, was considered but rejected for costs reasons.

Bearing housing

The greatest temperature gradient in the turbocharger arises between the turbine housing and the bearing housing. That is why an optimum connection of the two housings is so important to the service life of the turbocharger. The bearing housing was previously connected using clamping segments. This solution allows for a compact and economical design of the turbocharger. The tension strap was selected as a connecting element after taking the aspects of a secure connection for the housing, good thermal decoupling and a simple mounting procedure into account.

Due to the higher heat flux at 1050°C, the water cooling system of the bearing housing was optimized. The water core in the bearing housing was made larger and moved closer to the piston ring seat. In order to obtain optimal cooling properties, the open flow cross-sectional area was held constant as much as possible along the circumference. The placement of the water connections at the highest point on the bearing housing allow the unimpeded withdrawal of steam bubbles. The number of surfaces to be machined was also reduced through this measure. It is still possible to place the water connections on the side in addition to the water connections on the top of the bearing housing. The supply and return lines can be selected as desired.

Figure 8 shows the new generation of turbochargers to be used in the future for all gasoline engines regardless of how high the exhaust gas temperature is. The new series offered by BorgWarner Turbo Systems fulfills all requirements placed on a turbocharger for exhaust temperatures of 1050°C. In addition, the existing series of turbines with variable geometry was further refined for use in the new series at an exhaust gas temperature of 1050°C.

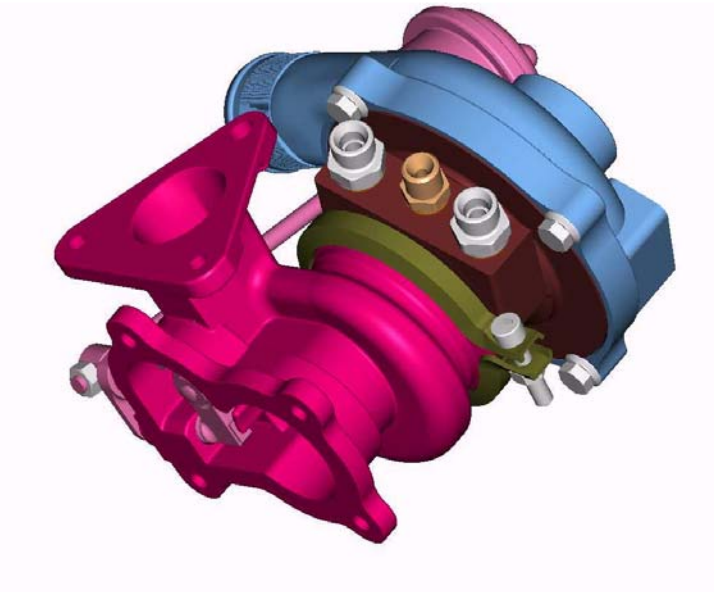

Figure 8: The new turbocharger for gasoline engines with exhaust gas temperatures up to 1050°C

Summary

- Future gasoline engines place the highest possible demands on the thermal load capacity of turbochargers. The exhaust gas temperatures at the turbine inlet will increase to 1050°C

- Future turbine housing materials include heat-resistant cast steel and heat-resistant sheet steel that place high demands on the manufacturing process.

- With the stamped steel turbine housing and the precision cast turbine housing, BorgWarner Turbo Systems offers two alternatives to reduce the weight and thermal inertia of turbine housings.

- Future turbine wheels for operation at 1050°C will be made of even higher quality nickel-based alloys than before.

- The bearing housing was redesigned with a highly efficient water cooling system in mind. The V-band clamp was introduced to ensure a secure connection between the bearing housing and the turbine housing at high temperatures.

- The existing turbines with variable turbine geometry will be refined for use at an exhaust gas temperature of 1050°C.

- The new generation of turbochargers for future gasoline engines made by BorgWarner Turbo Systems meets the highest demands of our customers in terms of thermodynamics, service life and cost. With this innovative turbocharger series we provide our customers with the ability to meet the demands that will be placed in the future on modern passenger cars in terms of fuel consumption, emissions and performance characteristics.

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