

Material Processing and Simulation Techniques for Automotive Systems

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OVERVIEW: Hitachi is engaged in the development and practical application of key technologies that underpin the development of automotive equipment and systems. These include material processing techniques that achieve light weight and low friction losses, thermal design and simulation techniques that allow miniaturization, and hydraulic simulation techniques that shorten development times and improve product quality. In the field of material processing techniques, Hitachi uses surfacing such as titanium nitride and DLC in pumps, lifters and other components and has developed the world's lightest brake calipers using FSW for welding. Hitachi has also applied its thermal design and simulation techniques to develop an inverter heat sink that uses direct water cooling and its hydraulic simulation techniques to develop a high-pressure fuel pump that uses a proprietary flow rate control mechanism to achieve the world's highest flow rate.

INTRODUCTION

IMPROVING the energy efficiency of vehicles has become a necessity, with particular requirements including the reduction of friction losses in sliding parts and weight reduction for mechanical parts. Hybrid vehicles are expected to play a decisive role in

responding to environmental issues and ensuring that this technology can be applied even in small vehicles requires that parts be made smaller and lighter, with improving cooling efficiency in particular being a prerequisite for miniaturization. There are also growing demands to shorten vehicle development times and

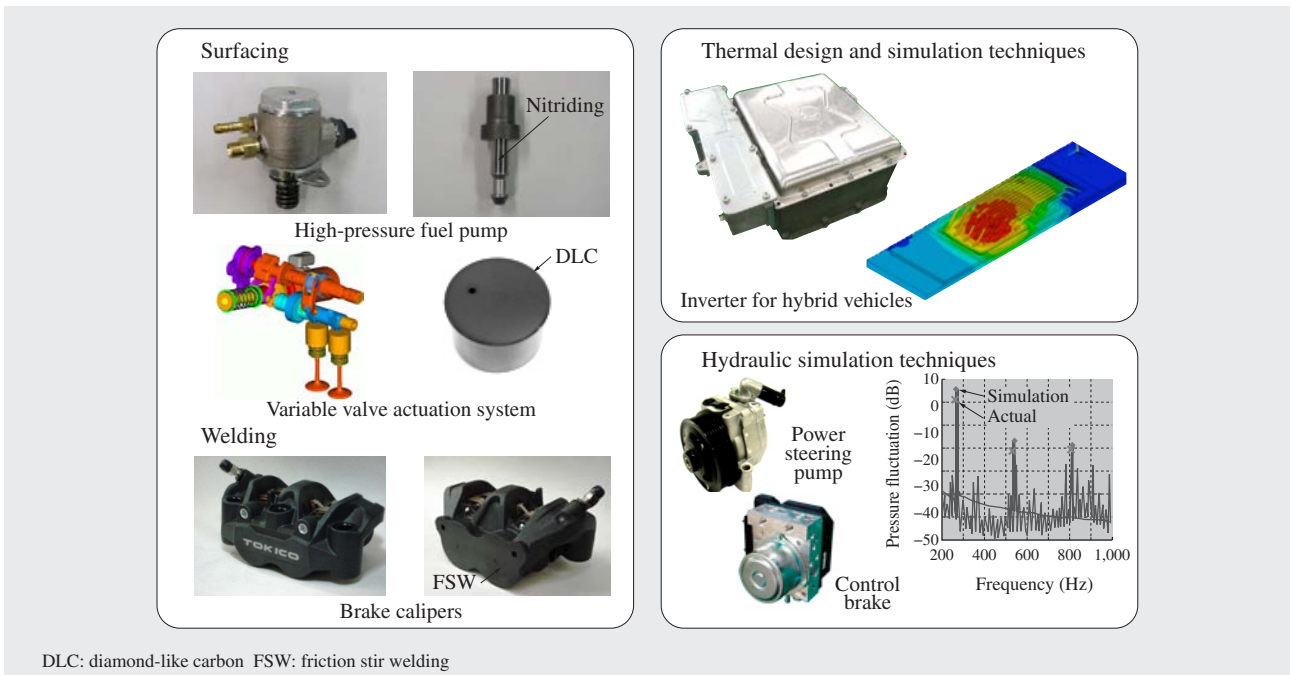


Fig. 1—Example Products Underpinned by Material Processing and Simulation Techniques. Hitachi uses materials processing and simulation techniques to develop engine control equipment, drive control equipment, and electric power train equipment.

this makes analytical design techniques especially important.

In response to these needs, Hitachi is working on the development of technologies for vehicle systems that aim to provide safety and comfort along with excellent environmental performance (see Fig. 1).

This article describes how Hitachi uses material processing and simulation techniques to support automotive systems and gives examples of how these techniques are applied in actual products.

MATERIAL PROCESSING TECHNIQUES

Only some of the energy contained in the fuel put into a car emerges as driving energy, with the remainder being accounted for by losses in the engine, mechanical losses in the drive train, and thermal losses in the exhaust system. In addition to engine efficiency improvements such as direct injection systems and variable valve actuation systems, techniques for improving energy efficiency include reducing the mechanical and friction losses in sliding parts and reducing driving resistance by making mechanical parts lighter. Adoption of these techniques depends on the cost-performance advantages they provide. The technologies behind the materials used in parts and other vehicle systems, specifically material processing techniques such as surfacing and welding, play an important role in reducing friction and weight.

Surfacing

Engines include a number of sliding parts and these are designed to ensure that parameters such as the sliding force, speed, and quantity of lubricating oil are appropriate. As the sliding materials operate under severe conditions, they require low friction as well as resistance to wear and corrosion. Such parts are typically made of heat-treated carbon or alloy steel. Once performance factors such as the friction coefficient or ability to avoid heat-induced sticking reach the limits of what can be achieved, it becomes necessary to apply surfacing such as hardening the surface layer of the material using diffusion treatments like carburized quenching and nitriding and by coating with a high-hardness material such as chromium nitride, titanium nitride, or DLC (diamond-like carbon) (see Fig. 2).

These surfacing techniques were developed for applications such as tools and dies that require wear resistance, good lubrication, and resistance to heat. When applying these techniques to automotive parts where reliability and durability are essential, it is important that the sliding material, surface heat treatment, and

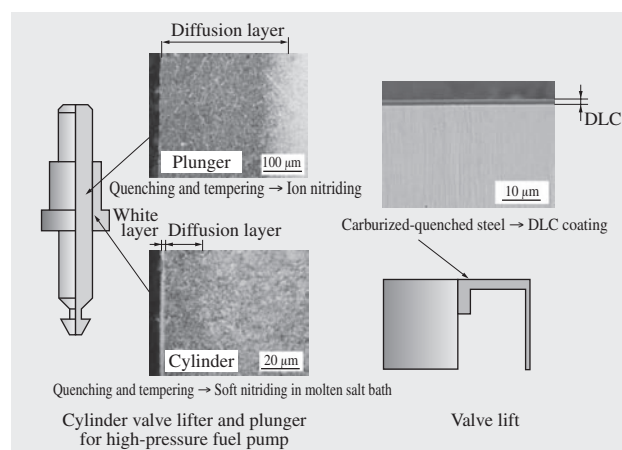


Fig. 2—Surfacing of Sliding Parts.

After heat treating the surface of the steel base material, the surface is further finish-hardened by diffusion treatments such as carburized-quenched steel and nitriding and by applying a hard film coating.

surface roughness be selected together.

The high-pressure fuel pump for direct injection engines originally had five fuel compression chambers but this was reduced to three and then one by miniaturization and the use of higher fuel pressure. This resulted in an increased load on the plunger that compresses the fuel and the cylinder that guides the motion of the plunger. The machining precision and wear resistance of these components is of particular importance for ensuring the pump discharge flow rate and advances have been made in material surfacing to achieve this. For the single-chamber pump, heat-treated alloy tool steel with excellent machining characteristics is used for the plunger and cylinder, and these are also subject to ion nitriding and soft nitriding in a molten salt bath to ensure wear resistance.

As future requirements will include resistance to wear by corrosion due to the wider range of fuels in use such as E85 and other ethanol blends, use of DLC coating will be investigated to take advantage of its excellent corrosion resistance.

The plunger and inlet and outlet valves in the high-pressure fuel pump have a cyclic motion driven via the lifter by the rotation of the camshaft. The cam is made of spheroidal graphite cast iron and the lifter is made of chromium-molybdenum alloy steel which has excellent cold forging and carburized quenching characteristics. Although the sliding parts of these components are immersed in engine oil, the small contact areas are subject to high loads and the elastic strain at the material surface cannot be ignored. This makes it important to consider elasto-hydrodynamic lubrication when designing the

oil film thickness. However, when the conditions under which the equipment is operating become severe, regions occur where the oil film is lost even when the surface roughness of the sliding parts is taken into account. This creates a region of boundary lubrication at the transition between where fluid lubrication is provided by the oil and where the parts are in direct contact, leading potentially to degradation of wear resistance and ability to avoid heat-induced sticking. With the aim of reducing the friction resistance of the sliding parts, Hitachi has investigated hard surface coatings such as chromium nitride and titanium nitride (which have a friction coefficient of about 0.4) or DLC (which has a friction coefficient of about 0.1). As the chromium-molybdenum alloy steel has a low heat treatment temperature of 200°C, the arc ion coating method which has a comparatively low coating temperature is used to apply a titanium nitride coating to the plunger lifter and a DLC coating to the valve lifter. The DLC formed by this process is hydrogen-free and has a film hardness of about 7,000 HV (Vickers hardness) which is significantly better than other types of DLC coating.

As engine oils and the additives used in them are becoming more diverse, Hitachi intends to conduct further investigation into hard coatings with excellent chemical stability.

Welding

Aluminum castings are used extensively for automotive parts and they are usually held in place by fastening bolts or screws. Although aluminum brake calipers used on motorbikes had a two-piece design held together by bolts, there is a demand for improvements in sensitivity as well as smaller size, lighter weight, and better stiffness in order to achieve the better brake performance associated with improvements in driving performance. In response, Hitachi has investigated using a plug-type monoblock design and using welding to join the separate parts into a single unit to improve functionality and performance (see Fig. 3).

It is difficult to weld aluminum castings efficiently using fusion welding because it results in voids caused by the condensation of gases trapped inside the casting. FSW (friction stir welding) on the other hand is highly suited to welding of aluminum castings because it uses solid state joining at a temperature below the melting point of the material and therefore does not form voids. FSW is already used on aluminum alloy body extrusions for railway carriages. FSW is used to perform a dissimilar material joining of the block, which uses an aluminum-copper-silicon cast, and the plug which uses wrought

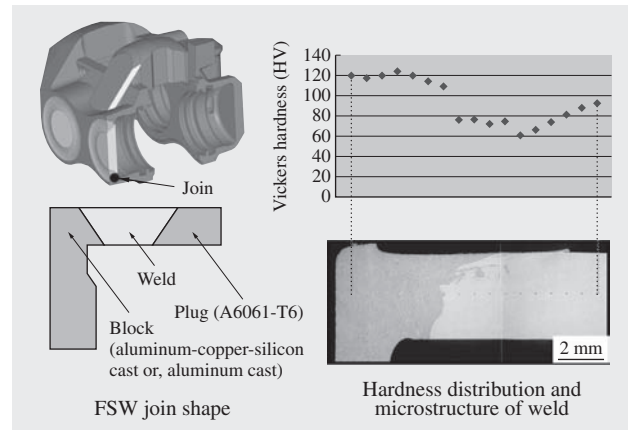


Fig. 3—Join Characteristics of Monoblock Caliper.

The weld is formed by mixing the cast and wrought materials without melting them in order to keep any loss of hardness to a minimum.

A6061-T6 aluminum. Even though FSW is a solid state welding technique, the workpiece is heated over 450°C at the weld center. Furthermore, the monoblock is small hence low heat capacity, so that the workpiece softening and its thermal distortion is concerned. As FSW forms joints by using friction heating between the material and the rotating tool to soften and mix the materials, the heat input depends on the tool speed and welding speed. In addition to optimizing these parameters, air cooling of the weld is performed to help dissipate the heat and achieves a drop of about 50°C in the temperature of the region around the weld.

By adopting a monoblock bolt-less design made possible by these welding and by replacing the steel piston with A6061-T6 aluminum, Hitachi has succeeded in developing the world's lightest brake calipers which weigh approximately 20% less than previous models.

Hitachi plans to apply this technology to aluminum brake calipers for four-wheel vehicles and to investigate use of plastic for pistons to reduce weight further.

THERMAL DESIGN AND SIMULATION TECHNIQUES

This section looks at cooling techniques for electrical parts used in hybrid vehicles. Improving the cooling capacity of the inverter in particular helps make the system smaller and lighter and is a way of reducing costs by allowing a smaller semiconductor chip to be used.

Direct Water Cooling

A power module consisting of an IGBT (insulated gate bipolar transistor) and diode, a ceramic insulating substrate, and a copper base are soldered together to achieve low thermal resistance between the power

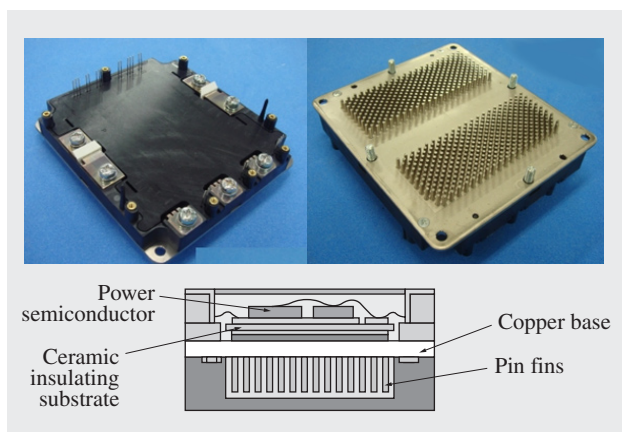


Fig. 4—Directly Water-cooled Power Module.

The pin-fin-shaped heat sinks on the underside of the module are formed as a single piece and improve cooling performance by dissipating heat through direct contact with the flow of cooling water.

semiconductor and the pin-fin heat sink (see Fig. 4). Although the different thermal expansion coefficients of the different materials result in thermal stress when the module temperature increases during use, this thermal stress can be minimized by controlling the equivalent thermal expansion rates of the insulating ceramic substrate to be midway between that of silicon and copper by fine tuning the thickness of the copper wiring layer bonded to either side of the substrate.

Thermal Simulation

As the losses (heat generation) in the power semiconductor depend on a number of factors including the amplitude and power factor of the current to the electric motor, the modulation index of the inverter, and the switching frequency, thermal stresses are generated by the resulting temperature fluctuations with the potential to cause fatigue failure in the connections. Accordingly, accurate simulations of the temperature changes that take place during inverter operation are required.

The thermal resistance and time constant were calculated based on the coupling analysis of how current and heat interact shown in Fig. 5 and used to simulate the temperature changes associated with the current patterns that occur in an actual moving vehicle.

HYDRAULIC SIMULATION TECHNIQUES AND EXAMPLE APPLICATIONS

Vehicles incorporate numerous different components that operate on hydraulic or fluid pressure. These include power steering, brakes, oil pumps, and fuel pumps. Hydraulic simulation is a key technology

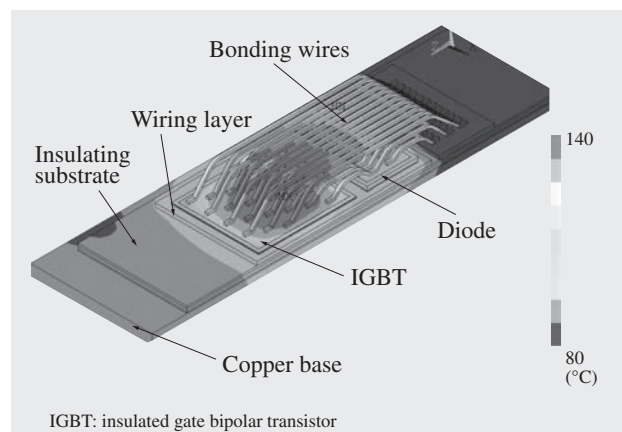


Fig. 5—Results of Simulation of Current/Heat Interaction. A detailed simulation of the temperature distribution was produced from a coupling analysis of how current and heat interact.

for the development of these components and helps shorten development times and improve the degree of completion of the resulting products.

This section uses a high-pressure fuel pump as an example. Fig. 6 shows the pump configuration and examples of hydraulic simulation.

The pump pressurizes the fuel to approximately 10 MPa and supplies it to the injectors via the common rail.

The hydraulic simulation uses a MATLAB/Simulink simulator to model the components and channels in the pump to a high degree of precision⁽¹⁾. The lower half of Fig. 6 shows the results of a simulation for an engine running at 2,000 min⁻¹ in terms of how the pressures, displacements, and flow rates vary with time at each part of the pump. The simulation allows a detailed understanding of what is happening inside the pump and assists with improving the performance of the pump and the development of pump control techniques and fuel rail designs that reduce pressure pulsations.

Fig. 7 shows an example of how the pump operating range was expanded by using this simulator to simulate the response time of the solenoid valve and optimize the drive signal accordingly. The solenoid valve opens and closes with each cycle of the plunger and its response time varies depending on the flow force exerted by the cyclic flow of the fuel. To deal with this, a study was conducted of the required drive signal durations by using the simulation to obtain these response times. The results indicated that the higher the pump speed or the lower the flow rate, the shorter the drive signal

* MATLAB and Simulink are registered trademarks of The MathWorks, Inc.

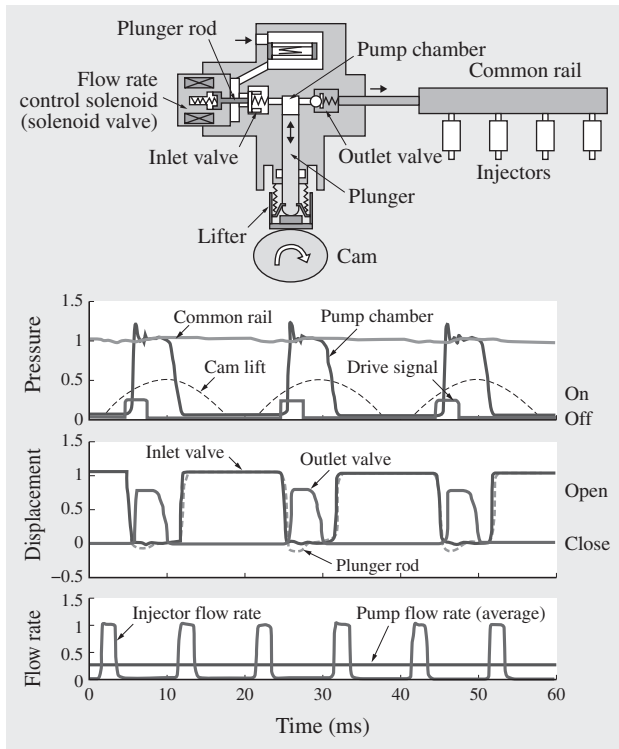


Fig. 6—High-pressure Fuel Pump and Example Hydraulic Simulation.

The simulation shows physical quantities that are difficult to measure, such as valve operation and the pressure inside the pump, and helps provide a detailed understanding of the sequence of operations in the pump.

that was needed. This meant that, by shortening the duration of the drive signal, flow rate control could operate at higher pump speeds while also reducing the power consumption of the solenoid valve.

CONCLUSIONS

This article has described how Hitachi uses material processing and simulation techniques in the development of automotive equipment and given examples of how these techniques are applied in actual products.

These techniques are essential to improving system efficiencies, shortening development times, ensuring product reliability, and reducing the size and cost of these products.

Hitachi intends to continue improving these techniques with the aim of developing even better products with even shorter development times.

REFERENCE

- (1) K. Hiraku, "Development of High Pressure Fuel Pump by Using Hydraulic Simulator," SAE Annual Congress 2005, SAE, 05P/85 (2005).

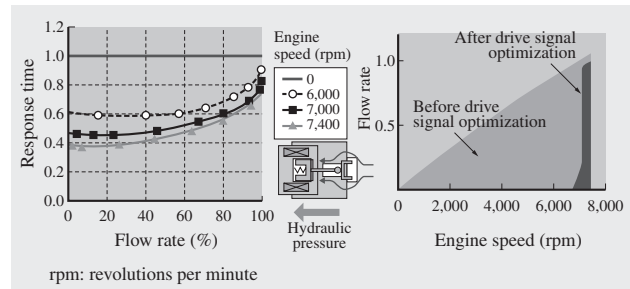


Fig. 7—Results of Simulation of Solenoid Valve Response and Optimization of Pump Operating Range.

The pump flow rate control range was extended to cover higher engine speeds by using hydraulic simulation to obtain the response time of the solenoid valve and then optimizing the drive signal duration with respect to rpm.

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