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Recent Technology Development of High-Powered Rotary Engine at Mazda

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ABSTRACT

In response to today's market demands, technological development for high-powered rotary engines has been under way for application to passenger models and racing engines.

This paper, describes first the development work devoted to achieve higher output, including a turbocharger system, tuned induction and exhaust systems, combustion chamber shape, ignition system.

New technologies used for components so as to cope with higher power output, thus securing engine reliability and durability are discussed.

Those technologies include a new surface treatment for improved lubrication of the trochoid surface, reduction in rotor gear stress, and optimization of the spark plug and igniter system.

Those development efforts resulted in production of: TURBO CHARGED 573 cc x 2 rotors, 165 ps/6500 rpm engine for passenger car and 573 cc x 2 rotors, more than 260 ps/9000 rpm engine and 654 cc x 2 rotors, more than 300 ps/9000 rpm engine for racing.

THE 1973 OIL CRUNCH gave a great momentum to technological development efforts at the author's company for improving Wankel rotary engine fuel consumption. It was made clear in the process that methods used control exhaust emissions have a major impact on its fuel efficiency. Thus the company switched from the preceding thermal reactor to the catalyst system, making possible the use of lean mixture with a roughly 30% fuel economy gain. New rotary engine models which are on the market today were developed from that system.

In response to recent market demands, technological development under way includes that of high-powered engines for passenger cars and also racing engines.

On the other hand, higher engine output brings with it higher thermal load in the combustion chamber along with increased mechanical stress and wear of the related parts. This calls for increased reliability and durability in terms of sliding parts lubrication and components' durability.

The important technologies developed to cope with those requirements are described in the following.

SURFACE TREATMENT ON Cr-PLATING OF TROCHOID

LUBRICANT RETAINABILITY ON TROCHOID SURFACE - When the engine is operated at high speed and high output, the trochoid surface being rubbed by the apex seal is subjected to high contact force, such as 150 kg gas force, at a maximum sliding velocity of 37 m/s. At the same time, the trochoid surface is exposed to high-temperature combustion gas, resulting in severe lubricating conditions. Also, it is in virtually line contact with the apex seal, which is another factor for the high bearing pressure. Such difficult lubrication conditions were overcome by developing a method to increase lubricant retainability of the Cr-plated surface which is prone to cause the shearing of oil film along with a method to provide metallurgical treatment to the apex seal's sliding surface.

Cr-plating has been developed and finally obtained as shown in Fig. 1, to the current most advanced pattern called the Micro Channel Porous (MCP) Cr-plating. MCP is formed over the conventional pinpoint porous Cr-plating by applying the reverse current to the plating electrodes so that the pinpoints can be connected with minute channels for improved lubricant spreadability as shown in Fig. 1.

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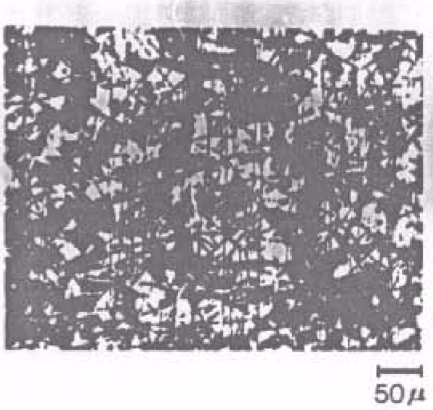


Fig. 1 Micro-channel porous Cr plating

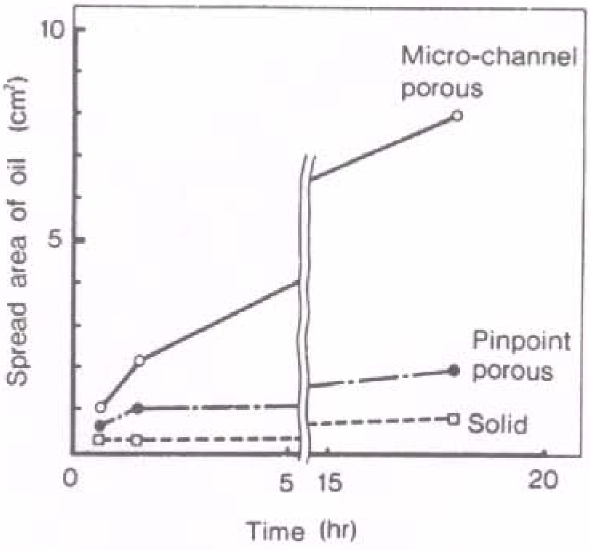


Fig. 2 Spreadability of oil with regard to Cr plate

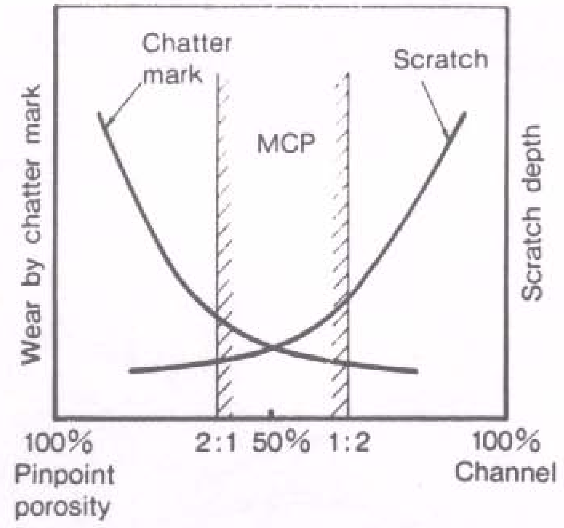


Fig. 3 Oil spreadability as a function of Cr plating pattern

Fig. [illegible] how lubricant spreadability on the trochoid surface differs as a function of procedures--solid, pinpoint porous, and MCP. Note that MCP provides excellent lubricant spreadability.

It was found meanwhile that MCP is effective on lubrication at a certain range of combinations of pinpoints and channels. As shown in Fig. 3, in respect to chatter marks across the trochoid and circumferential scratches, the best result is obtainable when the pinpoints to channels ratio is in the range of 1:2 through 2:1.

EFFECT OF INITIAL CONFORMABILITY TO TROCHOID SURFACE - As rotary engine output is increased by turbocharging and induction tuning, for example, it becomes necessary to keep better lubrication between the apex seal and the trochoid surface, especially when the engine is still in the green condition and is running under high-speed and high-load.

To meet this lubricating needs, a coating material with low friction coefficient, high lubricating performance and low cost was developed. Formulated by mixing a resin-base material with politetrafluoro ethylene (C_2F_4) and called Uncoherence Material (UCM), this very thin coat is applied over the Cr-plated surface and baked at a relatively low 160°C.

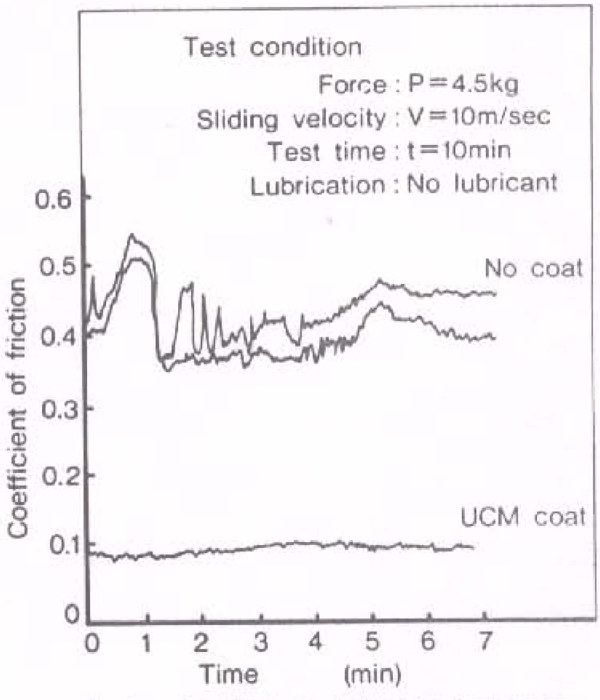


Fig. 4 Coefficient of friction between apex seal and trochoid

Fig. 4 shows the coefficient of friction between Cr-plated surface and apex seal. The UCM-coated surface shows a markedly low friction co-efficient compared to the uncoated surface.

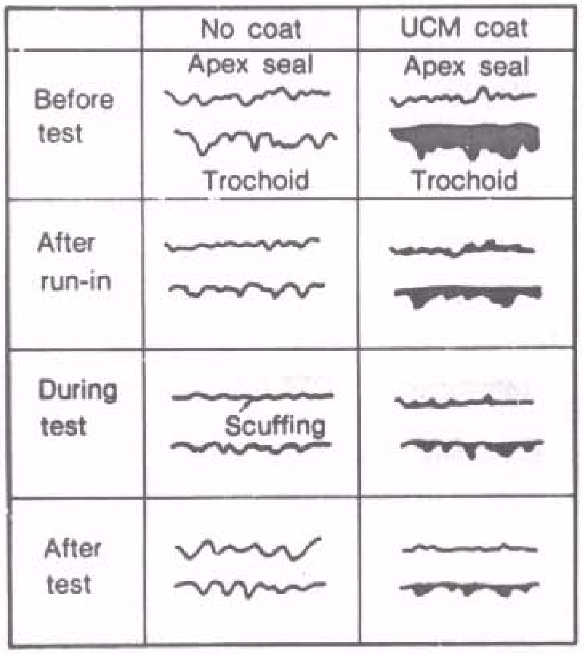


Fig. 5 Mechanism of conformability

In Fig. 5 shows a mechanism of conformability between apex seal and Cr-plating with and without UCM coat. In the case of no UCM coating, some scuffing appeared on the apex seal surface. Coating some 20μ of UCM over the trochoid was found to completely prevent abnormal wear of the apex seal even when an engine is operated under severe condition before running in.

TECHNOLOGIES TO INCREASE POWER OUTPUT

TURBOCHARGING SYSTEM FOR PASSENGER MODELS - From the 1984 model year, a turbocharged rotary engine with a fuel injection system has been used in passenger cars. (1)

With no exhaust valves, the rotary engine expels the exhaust gas rapidly, and the exhaust gas retains relatively high energy which is advantageous for turbine driving.

Absence of intake valves means less induction restriction resulting in high supercharging effect from low boost pressure. In addition, the intake stroke is 1 1/2 times as long as that of the reciprocating engine, which has the merit of lengthening the supercharging time.

Fig. 6 illustrates the turbocharging system used for the rotary engine. This turbocharger uses a new turbine blade shape as shown left side in Fig. 6 -- portion A of the blade which gas impacts first is straight with wider B area, while C section curvature is more pronounced. The advantage of this new shape is that the exhaust gas energy can be used more effectively for increasing torque and quick response at low and mid speeds.

This is the first production rotary engine with fuel injection. As shown in the left side, of Fig. 7, the injection nozzle, is located at the front and rear intake port to minimize injection lag. An air bleed adjacent to the nozzle is provided into which pressurized air is blown to provide fuel atomization. To further promote the atomization of fuel when it is fed in large quantity, a plastic plate with numerous tiny holes cut out is provided in front of the nozzle tip.

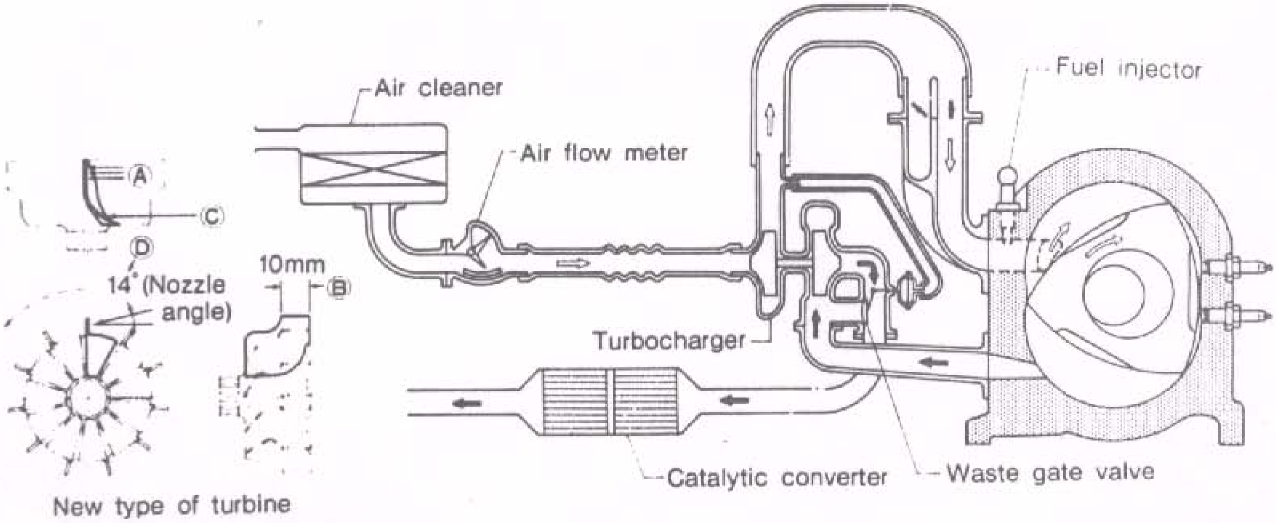


Fig. 6 Turbocharged rotary engine

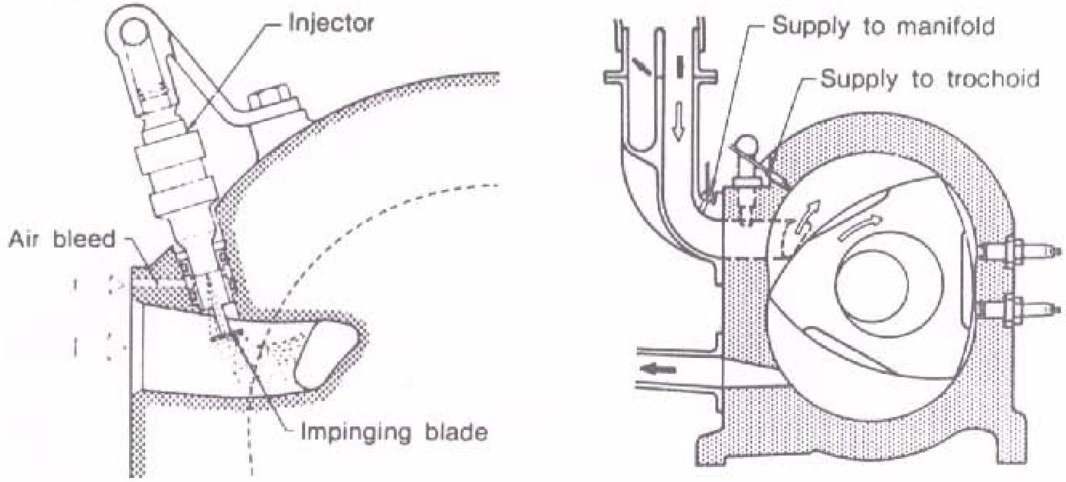


Fig.7 Fuel injection mechanism and oil metering system

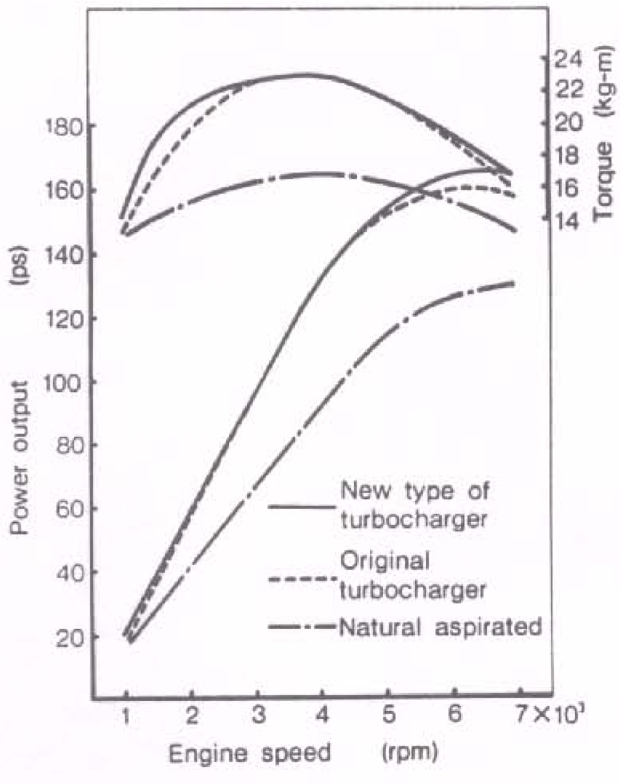


Fig.8 Performance of turbocharged rotary engine

In addition, to cope with the increased need for trochoid lubrication, the lubricant metering system was changed to a design where lubricant is fed at two points, i.e., into the manifold upstream of the nozzle and directly into the combustion chamber through the trochoid wall as shown right side in Fig. 7.

The output performance of the turbocharged engine described above is shown in Fig. 8.

PASSENGER CAR HIGH POWERED ROTARY ENGINE WITH NEW INDUCTION SYSTEM

DYNAMIC SUPERCHARGING EFFECT - A high-power rotary engine was realized by developing a dynamic supercharging induction system which uses interference of two kinds of compression wave:

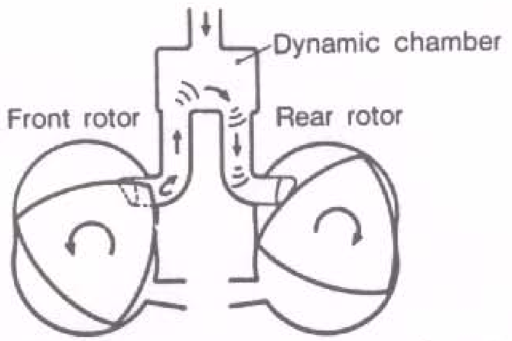
(1) As the intake port begins to be closed, air pressure rises due to its own inertia as shown in the top of Fig. 9. The high pressure creates pressure wave, which moves back up the intake pipe at the speed of sound, and down the other intake pipe to feed more air into the other port.

(2) As shown in the bottom of Fig. 9 the residual exhaust gas, which still has high pressure, is blown up through one of the intake ports and pushes against the intake air momentarily,thus raising air presure. As a result, a high pressure wave is sent down the other intake pipe, cramming more air into the other intake port.

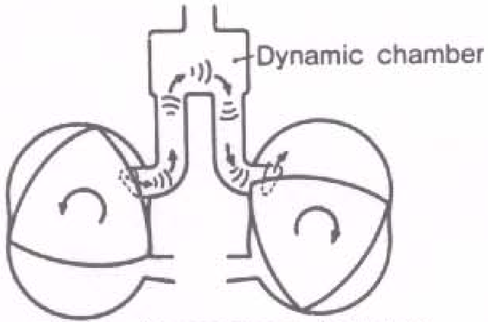
The above-mentioned effects are shown as the measurements of actual intake pressure waves in Fig. 10. A represents the effect of (1) interference of intake air and B is (2) interference of exhaust with intake air. These effects of interference came to reality through the installation of a dynamic chamber illustrated in Fig. 9.

VARIABLE INTAKE PORT TIMING EFFECT - Volumetric efficiency was enhanced by providing variable intake port timing in accordance with engine operation, thereby varying the rpm zone where the dynamic effect is generated.

This was made possible by employing a six-port induction system (6PI) that features the variable intake port timing. As shown in



Effect of interference between front and rear rotor



Effect of interference between intake and exhaust

Fig.9 Principle of dynamic effect on volumetric efficiency

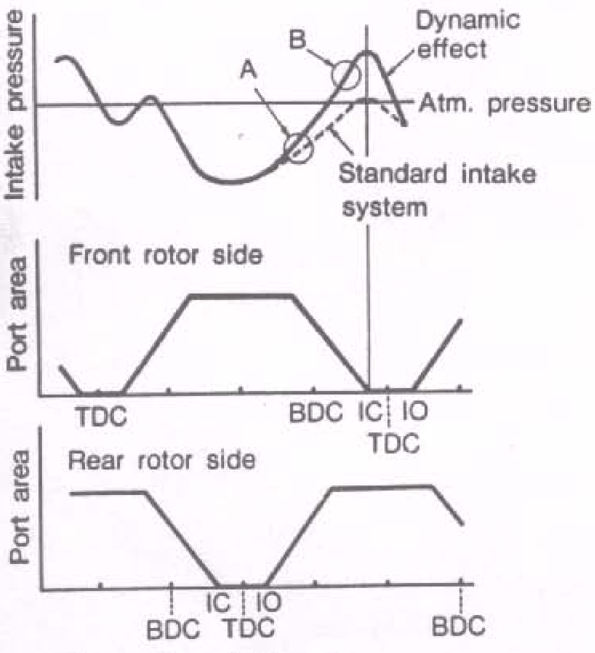


Fig.10 Intake pressure wave

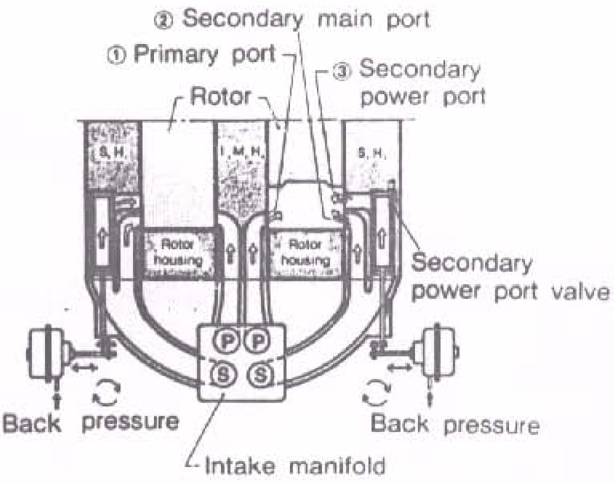


Fig.11 6 port induction system

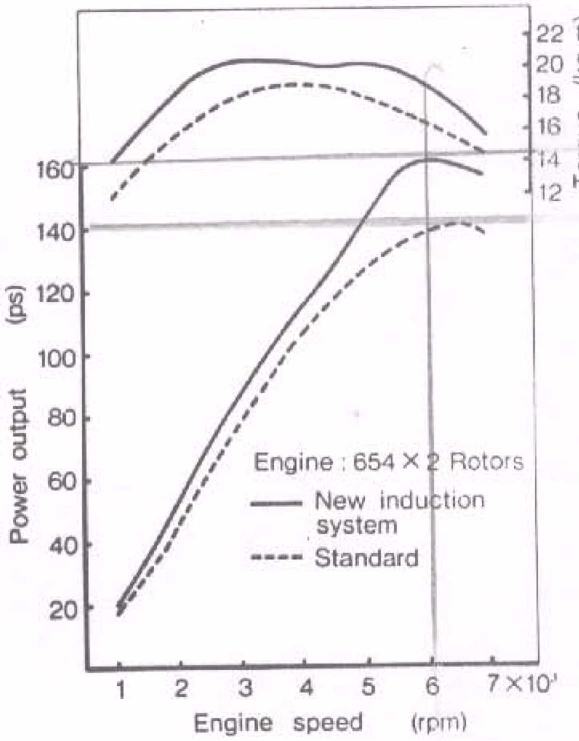


Fig.12 Engine performance of new induction system

Fig. 11, the intake porting consists of a primary port, secondary main port, and secondary power port.

The secondary power port is controlled by an internal cylindrical valve with a window, which is rotated by the exhaust pressure, thereby providing variable control of intake closing timing and port area.

OUTPUT PERFORMANCE - The two-rotor engine with single chamber volume of 654 cc equipped with this new induction system achieves high power output as shown in Fig. 12.

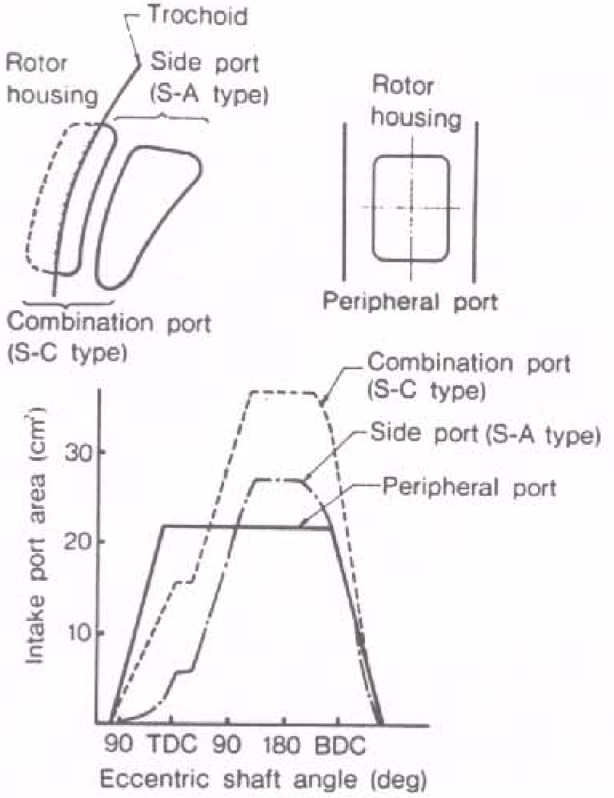


Fig.13 Intake port angle area

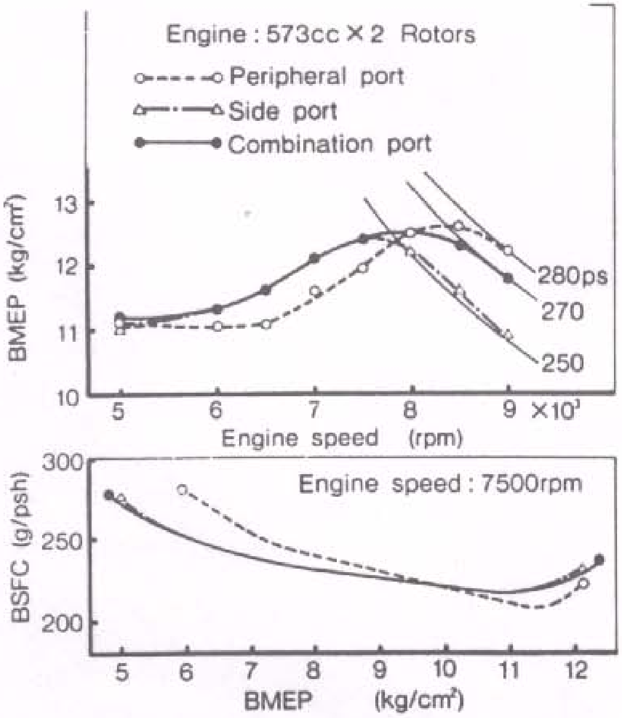


Fig.14 Out put and fuel consumption performance in relation to intake port type

ROTARY ENGINE TUNED UP FOR RACING - A high-power engine for racing was developed by tuning up the intake and exhaust systems.

Regarding the configuration of the intake and exhaust systems, the unique construction of the rotary engine offers particularly large flexibility in designing and tuning. Another advantage is the absence of reciprocating parts, which is beneficial to high-speed R.P.M.

THE FOLLOWING describes the intake and exhaust port configuration, port opening and closing timing, manifold pipe lengths, and combustion chamber configuration, along with increased power output obtained.

INTAKE PORT CONFIGURATION - Because of its relatively large freedown of intake system design, the rotary engine has an advantage in selecting optimum configuration and position of the intake porting, to provide high volumetric efficiency.

Fig. 13 shows evaluation of the three types of intake port: the peripheral port, the side port (S-A type) and the combination port (S-C type) having an additional peripheral port. The output characteristics and fuel consumptions of the three port types are compared in Fig. 14.

The peripheral port excels the side port at the maximum power but loses on low and mid speed range as shown in the top of Fig. 14. also the peripheral port makes the engine more sensitive to exhaust back pressure because of increased intake-exhaust overlap, resulting in considerable volumetric efficiency drop in the mid speed range.

Between the S-A type, i.e., side port with an additional side area, and the S-C type, i.e., combination port, there is a difference in the port area relative to the eccentric shaft angle, as shown in Fig. 13, which influences the volumetric efficiency. That is, the S-C type with the largest opening area produces the highest level of output in the mid and high speed range.

The peripheral port, though advantageous in highest power at high speed range, suffers in fuel consumption as shown in the bottom of Fig. 14. This is because the greater overlap of intake and exhaust increases exhaust dilution of inducted air, resulting in irregular combustion.

EFFECT OF PORT TIMING - Apart from the port shape, the opening and closing timings of ports, especially the intake ports, has great effect on volumetric efficiency. An instance of peripheral intake porting is reviewed below.

Intake port opening timing (IO) and closing timing (IC) in the trochoid surface were given in the manner shown in Figs. 15 and 16.

When IO timing is varied in the range of from 50 deg to 100 deg BTDC with IC timing fixed at 70 deg ABDC, volumetric efficiency in Fig. 15 resulted. As IO is made earlier, volumetric efficiency rises, but too early IO causes the intake-exhaust overlap to increase to such a level where the interference by the exhaust pressure comes to saturate volumetric efficiency gain. Thus it was found that the highest volumetric efficiency is obtainable by opening the intake port at around 80 deg BTDC.

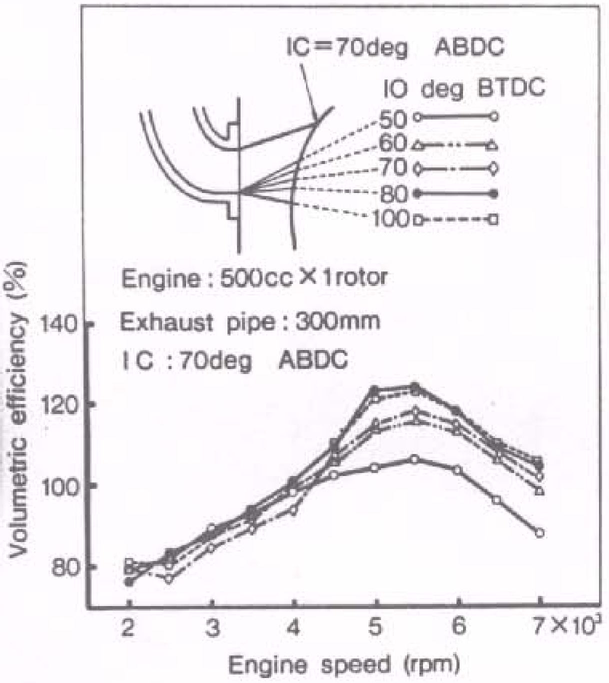


Fig.15 Effect of intake port opening timing on volumetric efficiency

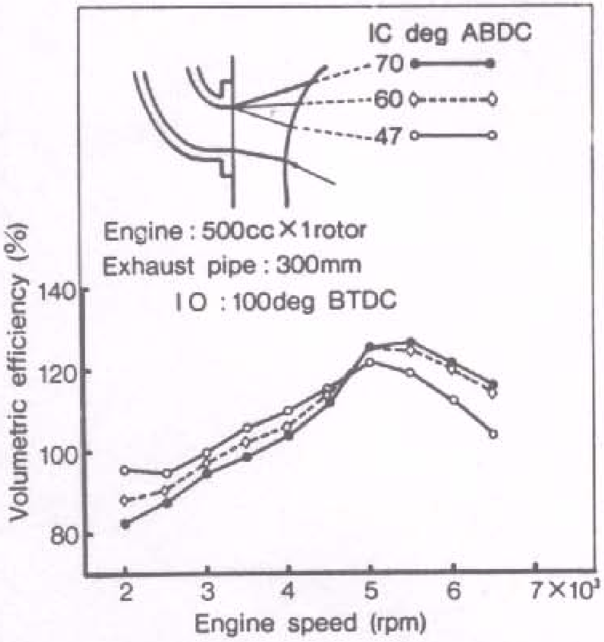


Fig.16 Effect of intake port closing timing on volumetric efficiency

When IC timing is varied in the 47 deg - 70 deg ABDC range with IC timing fixed at 100 deg BTDC, volumetric efficiency varied as shown in Fig. 16. The highest volumetric efficiency can be obtained at an IC of 70 deg ABDC. At any of these IC timings, volumetric efficiency falls in the engine speed range below the rpm at which the peak of efficiency is obtained. Consequently, in the racing engine aimed for maximum horsepower, 70 deg ABDC was chosen.

With IC fixed at 70 deg ABDC where maximum output was obtained at 6500 rpm, a pressure gauge was attached each at the intake and exhaust ports to measure pressure waves. The result is shown in Fig. 17. The intake port closes when the intake pressure wave reaches the peak, indicating high volumetric efficiency being obtained. On the exhaust side, negative pressure wave is created at the intake-exhaust overlap, with the effect of helping pull in more air.

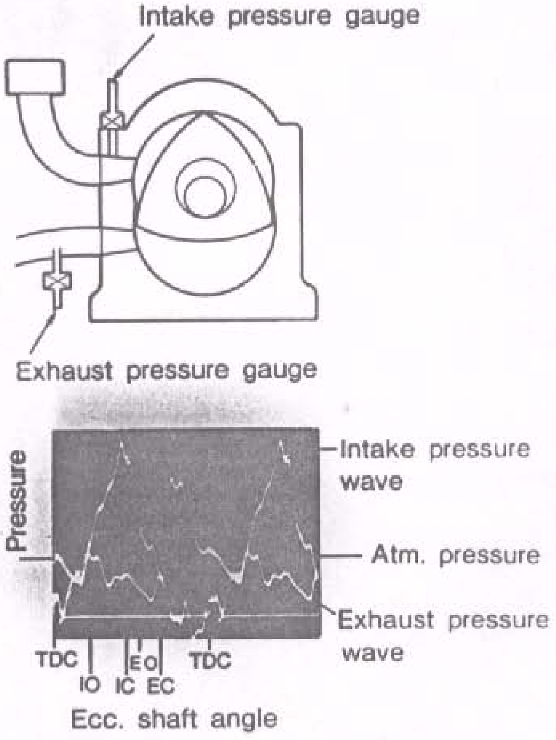


Fig.17 Intake and exhaust pressure wave

EFFECT OF INTAKE AND EXHAUST PIPE LENGTHS - Intake and exhaust pipe lengths have an especially significant effect on output performance when exhaust pressure is low and at the same time the intake-exhaust overlap is large. An investigation was made using a 500 cc single-rotor engine.

First, using an exhaust pipe ϕ44 x 1000 mm, intake pipe length was varied to 170 mm, 220 mm, and 370 mm to see how the output characteristics are influenced, as shown in Fig. 18. Increasing the pipe length resulted in increase in maximum torque, followed by rapidly decreasing torque at high speeds. Conversely, reducing the pipe length led to increase in maximum horsepower, although it was accompanied by falling torque in the mid-and lower-speed range is decrease.

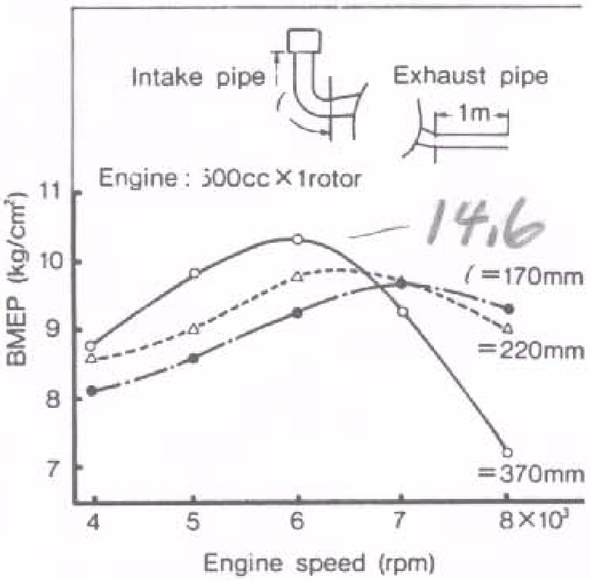


Fig.18 Effect of intake pipe length on engine performance

Variation in the exhaust pipe length brings about even greater influence on output characteristics. Fig. 19 shows output characteristics as determined by changing the pipe length from the exhaust port in the 50 mm - 1560 mm range. And it was found that many complicated dynamic effects appear as a function of pipe length and can be utilized to select an output characteristic as needed.

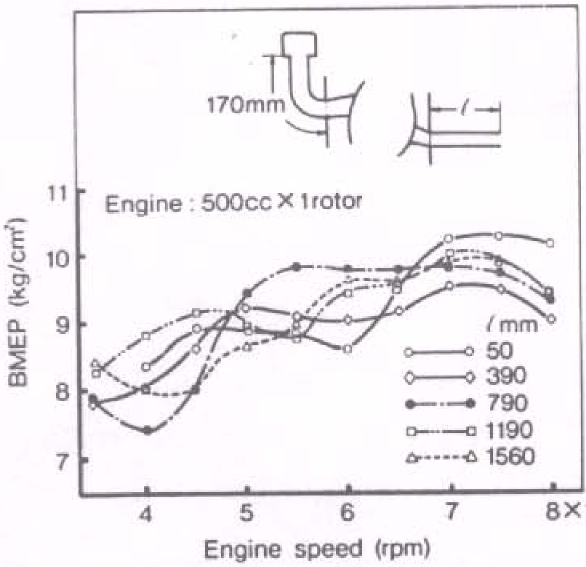


Fig.19 Effect of exhaust pipe length on engine performance

COMBUSTION RECESS CONFIGURATION AND OUTPUT - Selection of the combustion recess configuration relative to power output performance depends largely on location of the spark plug. In this testing, the trailing-side spark plug was located at 30 mm from the minor axis and the leading-side spark plug at 18 mm from the minor axis.

Comparative study was conducted on four types of combustion recess (MDR, LDR, L-Flat, T-Flat, and TDR) as illustrated in the top of Fig. 20.

In the case of the two-spark-plug ignition, MDR with the recess in the middle produced the best result, as shown Fig. 20. This configuration can be said to be optimally located in relation to the positions of the two spark plugs.

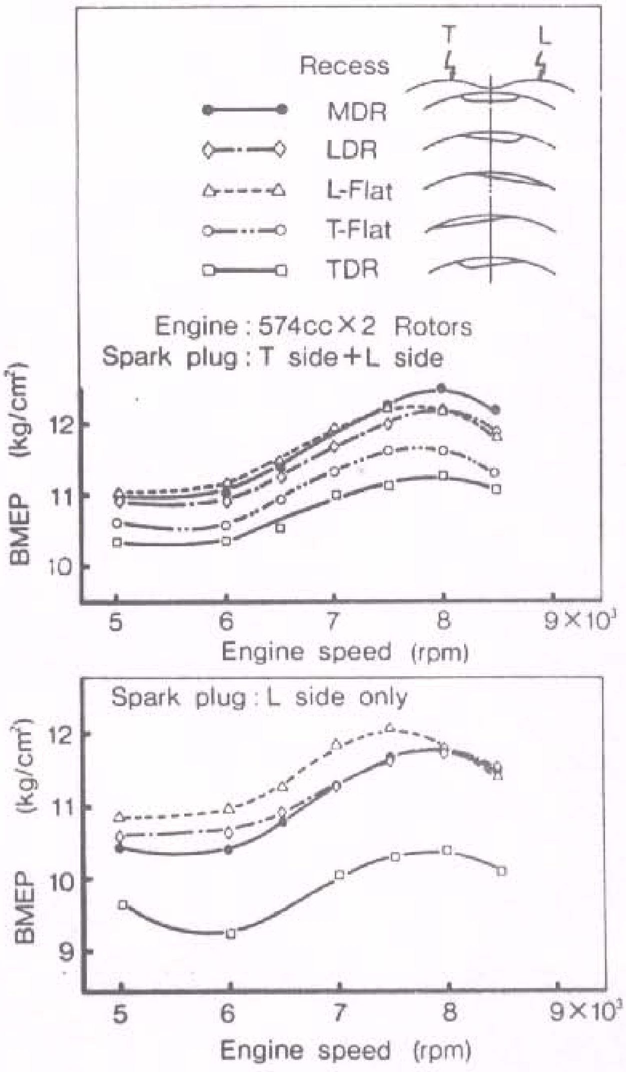


Fig.20 Effect of combustion chamber recess on engine performance

790/25,4 = 31"

The lowest output was recorded by TDR with the recess shifted toward the trailing side. This is probably because the major portion of combustion gas is on the trailing side to which the flame front reaches with less ease than to the leading side, resulting in incomplete combustion.

In contrast, LDR and L-Flat with the recess shifted toward the leading side produce considerably higher power than TDR though inferior to MDR.

When only the leading spark plug is ignited, a different tendency appears as shown in the bottom of Fig. 20; L-Flat and LDR put out more power than MDR, while TDR produces less power than with two spark plugs.

Since the two-plug system is in use to meet practical requirements, the MDT configuration is employed in the current rotary engines.

COMPONENTS STRENGTHENED TO COPE WITH HIGH POWER

ROTOR GEAR - One of the engine's internal parts which undergo most severe impacts during high rpm and high output is the rotor gear. The rotor gear was previously fixed to the rotor by nine resilient springpins so that the rotor gear teeth could withstand the high stress generated by the explosion and the rotor's torsional vibrations. Applying strain gauges on the rotor gear shaft, the load imparted to the gear was measured with nine and 12 spring pins. The result is shown in Fig. 21 as the rotating load and the reverse-rotating load. In the case of the nine spring pins, the load steeply increases from a resonant frequency of some 9000 rpm. When 12 spring pins are used, the load applied to the gear decreases by 25% - 50% with relatively mild load changes through 5000 - 9500 rpm. This is how the 12 spring pins came to be used.

APEX SEAL - The apex seal's sliding characteric is important when engine is operated under high output. Photo 1 shows the two kinds of apex seals for racing engine, one is a 2-piece type and made of special cast iron with its sliding surface chilled by electron beam. The other is a 1-piece type, is made of carbon for better self-lubrication characteristic and is impregnated with aluminum for higher strength. Both are 3 mm wide. The carbon apex seal is rather suitable for high-powered rotary engine because of its excellent lubricational ability under serious running condition.

IGNITION SYSTEM - As engine speed and load increase, the spark plug undergoes higher thermal load, and this makes high durability and ignitability critical requirements, calling for proper construction with high heat value as well as for suitable electric power supply.

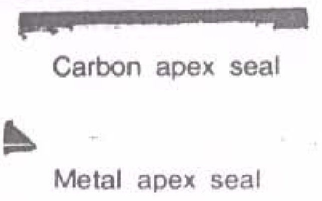


Photo 1 Apex seals for racing engine

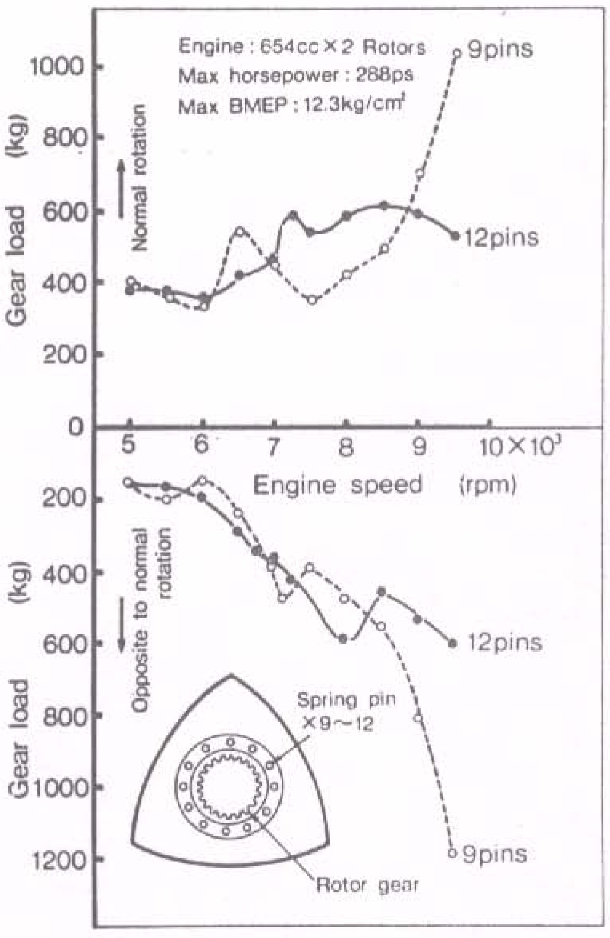
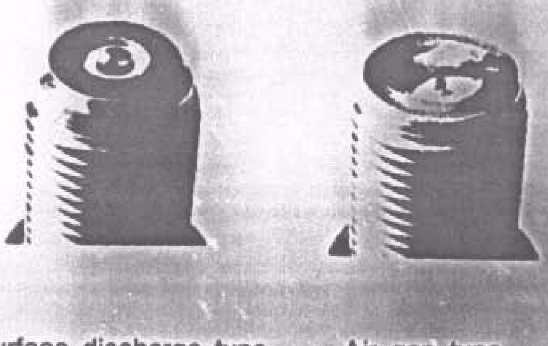


Fig.21 Load on rotor gear

Generally, ignitability by the spark plug can be increased by 1) using wider electrode gap and 2) positioning the electrode as close to the combustion chamber as possible. With the above taken into consideration, two spark plug shapes as shown in photo 2 were chosen. When these spark plugs are used, higher secondary voltage is required in order to get a strong spark. Thus, two kinds of ignitors were selected, that is 1) High Energy Ignitor (HEI) with increased-capacity and 2) Capacitive Discharge Ignitor (CDI). The secondary voltages required of the two spark plugs are shown by the broken lines in Fig. 22. The solid lines in the same figure show the ignition capacity of the two ignitors, indicating the need to use a suitable ignitor for each of the spark plugs.



Surface discharge type (S.D.)

Air gap type (A.G.)

Photo 2 Spark plugs for high performance engine

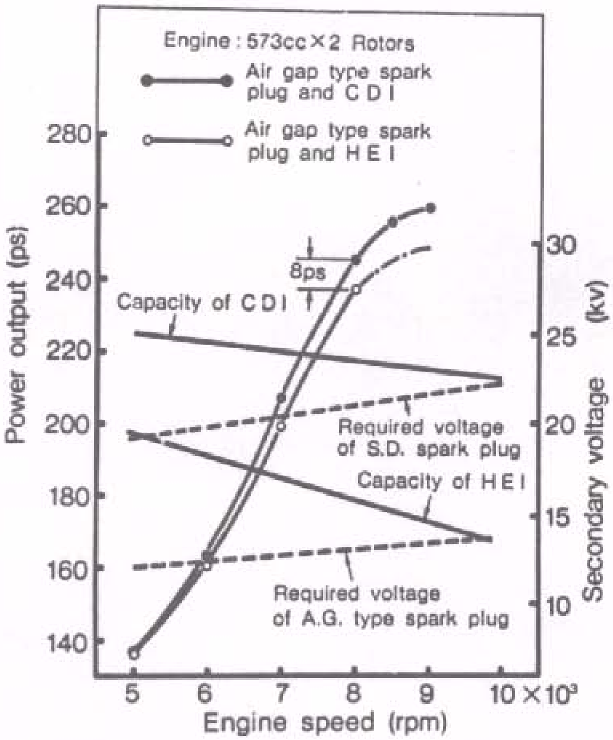


Fig. 22 Ignition system and performance

The air gap type spark plug was operated with the CDI and the capacity-upped HEI for comparison. The resulting power output characteristics shown in Fig. 22 indicate that CDI exceeds HEI in power output.

On the supposition that the reason for this power difference is the difference in secondary voltage generating capacity between the two power supply systems, HEI voltage was raised to the level of CDI but this resulted in no output increase. Consequently, the cause for this is considered to be difference in discharge pattern and in secondary current.

SUMMARY

Design and development work has led to commercial production of two new rotary engines for passenger models: a 573 cc x 2 rotors turbo-charged rotary engine deliverying 165 ps at 6500 rpm and a 654 cc x 2 rotors new induction system engine putting out 160 PS at 6000 rpm.

Two more new engines have been introduced as racing engines: a 573 cc x 2 rotors engine giving more than 260 ps at 9000 rpm and a 654 cc x 2 rotors giving more than 300 ps at 9000 rpm.

These high-powered rotary engine have been put into practical use by developing various components with higher reliability and durability especially the apex seal, rotor housing, rotor gear, and ignition sysem.

Specific technologies developed for that purpose include:

1) lubrication control by microchannel porous Cr-plating over the trochoid,
2) UCM coat for improving Cr-plating conformability with the apex seal,
3) rotor gear stress reduction, and
4) new-type spark plug improve in ignitability, fouling resistance, and durability.

ACKNOWLEDGEMENT

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