Material Technology Development Applied to Rotary Engine at Mazda

Takumi Muroki
and Jun Miyata
Mazda Motor Corp.
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ABSTRACT

New material and processing technologies were developed for main components of the rotary engine to establish its reliability and durability.

The components discussed in this paper are the rotor housing, side housing, and sealing elements. Also described are the material and processing technologies which resolved problems about their strength, rigidity, wear, etc.

INTRODUCTION

The Wankel type rotary engine (called merely RE in the remainder of this paper), undergoing all kinds of driving experience as an automobile engine, has continued to grow and mature for nearly two decades.

It can be said that material technologies, among others, have contributed much to the RE's reliability and durability.

The considerable difference of the RE in construction and operation from the conventional piston engine (called just CE hereafter) necessitated development of new technologies in materials and processing. The results of the development work are presented in this paper.

ROTOR HOUSING

The rotor housing, which is equivalent to the CE's crankcase and cylinder head assembly, is operated under severe thermal and mechanical conditions. Especially during the expansion stroke it is exposed constantly to combustion gas of high temperature and pressure. Fig. 1 shows temperature distribution over the circumferential trochoid wall at 5000 rpm WOT for an aluminum alloy and cast iron.

The cast iron shows greater durability in terms of strength, rigidity and thermal expansion at high temperature, but it is inferior in heat conductivity. In the case of cast iron, the trochoid surface on which the apex seal slides becomes too hot to retain a lubricating oil film, as will be noted from Fig. 1.

Thus an aluminum alloy was employed for heat conductivity with much effort expended to develop better materials, structure, and surface treatment.

5000rpm WOT
BMEP=686kPa

--- Cast iron ------ Aluminum alloy

Fig. 1 Comparison of temperature distribution

STRUCTURE OF ROTOR HOUSING - The rotor housing, restricted on both sides by tension bolts through the side housings, is subjected to heating and cooling. This makes it susceptible to cracks due to thermal fatigue, originating at the shooting hole of the spark plug under very severe operating condition. In addition, being clamped tightly between the side housings, the rotor housing could suffer axial compressive deformation with possible durability problems.

Development work for materials having increased durability against thermal fatigue in particular was conducted using a thermal fatigue tester. Aluminum alloy specimens (permanent mould) were given cyclic thermal loads ranging from 20 - 250°C until the rotor housing cracked and broke, and evaluation was made based on the number of cycles registered until the breakage occurred. An example of the test result is shown.
Investigation of material compositions and heat-treatments led to adopting, as the base metal of the rotor housing, a T-6 treated aluminum alloy AC4D (Si 5.0%, Cu 1.2%, Mg 0.5%).

The trochoid surface on which the apex seal slides is given hard chrome plating to provide good wear resistance. To prevent the chrome plating from fatiguing and peeling off under the apex seal's vibrating load, study was made on how to provide a better trochoid surface for chrome plating adhesion. As a result a new process called SIP (Sheetmetal Insert Process) was developed.

As shown in Fig. 3, the aluminum rotor housing is die-cast under high pressure to the trochoid-shaped sheetmetal with one side jagged in the saw-tooth manner for better bonding with the aluminum alloy. The SIP rotor housing offers a markedly improved surface insuring proper adhesion of chrome plating.

The effect of this development was evaluated using a contact rolling fatigue tester in which a loaded test piece is rolled as shown in Fig. 4. Fig. 5 indicates that SIP offers ample adhesion to the chrome plating.

**Fig. 3** Cross section of trochoid surface

**Fig. 2** The strength of Al alloy for rotor housing

**Fig. 4** Schema of contact rolling fatigue test

**Fig. 5** The adhesion life of Cr plating by contact rolling fatigue method

CHROME PLATING: Rubbing by the apex seal used to cause the trochoid surface to develop the so-called chatter mark - ripple marks and scuffing.

To overcome this problem, study was made on material of the apex seal and chrome plating of the trochoid surface.

The electroplating procedures studied for surface-treating the trochoid surface included nickel plating containing silicon carbide, cermet spray, and chrome plating, and this last was adopted for quality and productivity.

The chrome plating has a Vickers hardness of more than 1100. Furthermore, the chrome plating, which in characteristically poor in wettability with oil, is provided on its surface with minute pores and channels for effective oil retention.

As shown in Fig. 6, the chrome-plated surface is given electro etching and honing to make it pinpoint-porous, followed by another electro etching which produces micro-channels [1]. This micro-channel porous (MCP) plating is effective in maintaining oil film and reducing the friction with the apex seal. Note from Fig. 7 that the MCP plating possesses far greater oil spreadability relative to the pinpoint porous plating [2].

* Number in parentheses designate references at end of paper.
APEX SEAL

Early in the development stage the RE used a composite one-piece apex seal made of carbon impregnated with aluminum. It was replaced later by a two-piece apex seal to provide better gas sealing, with the material changed to a stronger one in the form of cast iron.

The top surface of this apex seal that slides on the chrome plating shown in Fig. 8 is melted by electron beam and rapid solidified to provide an approximately 1 mm chilled layer.

The chilled layer has excellent anti-friction properties since it contains a crystallization of finer cementite than is obtainable by ordinary chill casting. The base metal of the apex seal is acicular cast iron with bainitic structure. In addition to offering high strength and ductility to the apex seal, this structure gives increased wear resistance to its side faces (where it contacts with the apex seal groove walls) and its end faces (where it contacts with the side housing).

APEX SEAL TEMPERATURE - Since lubrication between apex seal and trochoid is an important factor of engine operation, it was necessary to learn the apex seal's temperature distribution during operation with respect to oil film formation.

The amount of the necessary lubricant for the lubrication between apex seal and trochoid surface has a close relation to the apex seal temperature, as shown in Fig. 9 [1].

The suitable amount of the lubricant is that of when apex seal temperature begins to rise up due to the lack of the lubricant.

From this point of view, the apex seal temperature was measured to know how the temperature changes during engine running.

Apex seal temperature measurement was conducted by the following procedure. A thermistor is embedded in the temperature-measuring portion of the apex seal, and, its lead wire goes through the rotor, as shown in the top portion of Fig. 10. The signals are taken out via the meshing of the internal gear fastened on the rotor with the stationary gear on the housing, as shown in the bottom of Fig. 10. The signals in current are converted to temperature changes.
1. TEMPERATURE OF BOTTOM AND TOP OF APEX SEAL - Temperature was measured at the top and bottom of the apex seal: as shown in Fig. 11, the temperature of the apex seal rises in accordance with the engine revolution, however at 5000 rpm with high load the apex seal temperature is reduced, because the combustion gas temperature is reduced by setting of richer mixture at high load. The temperature difference between top and bottom was below 10°C as shown in Fig. 11.

2. APEX SEAL'S AXIAL TEMPERATURE - Temperature was taken at the middle and both ends of the apex seal as shown in Fig. 12. It is to be noted that the heat flux into the seal flows to the side housing and rotor housing, indicating that the heat transmitted to the side housing exceeds the heat transmitted to the trochoid surface because of wider contact area of the end surface of the apex seal.

3. TEMPERATURE IN TRANSIENT CONDITION - Fig. 13 plots temperatures that the apex seal registered when the engine was accelerated from 1000 rpm under no load up to 5000 rpm WOT and held at this speed for 45 seconds before it was decelerated to 1000 rpm under no load.

At 1000 rpm at no load, the apex seal's top was lower in temperature but became hotter during acceleration, and during deceleration it became less hot than the bottom.

SIDE HOUSING

The side housing's inner wall is rubbed by the corner seal, side seal, oil seal, and rotor flank. This associated rubbed surface is in face contact and represents a considerable bearing area, with relatively generous supply of lubricating oil. Thus the side housing's operating condition is favorable compared to the rotor housing's.

However, as the engine is made capable of higher speed and power output, the thermal load rises, causing its operating condition to become less favorable, with the result that the oil
seal lip in particular suffers increased wear, thus increasing oil consumption. To solve such problems, the plain cast iron surface of the side housing was softnitrided with resultant improvement in wear resistance and anti-corrosion.

![Cross section of soft nitride layer](image)

**Fig.14 Hardness of soft nitriding side housing**

In this process the side housing is soaked in a 570°C atmosphere of ammonia and RX gas for three hours to form on the cast iron surface an 8 - 10μ FeN compound layer—an extremely hard metal surface. The photo in Fig. 14 shows the section of the surface structure. Vickers hardness values of different-depth sections, in Fig. 14, indicate that hardness is low in the base metal, increases in the diffusion layer, and steeply rises in the top compound layer. The side housing inner wall thus obtained contributed greatly to improved friction characteristics with the associated sealing elements as well as improved wear performance, as will be given later in some detail.

**CORNER SEAL**

The corner seal must be of such a material as does not induce scuffing on the side housing as it slides on it at high speed and load. A material selected is flaky graphite cast iron containing phosphorus and boron. This cast iron, as shown in the right photo of Fig. 15, is highly resistant to seizure and wear, being of a structure with hard steadfast and carbide dispersed in the pearlite matrix.

The corner seal periphery is chrome-plated, as shown in the left column in Fig. 15, to prevent fretting wear between the corner seal and the peripheral surface and the wall surface of the corner seal groove in the rotor.

![Fig.15 Configuration and microstructure of corner seal](image)

**SIDE SEAL**

The side seal, as in the case of the corner seal, is made of a material which has the effect of reducing friction. But it is thin, long, and arc-shaped; its entire face must always be in contact with the side housing inner surface, and in addition its entire lateral surfaces are required to be in contact with the walls of the side seal groove. This calls for precision-made side seals. With the cast iron, productivity was found poor for precision machining. Thus a sintered-metal side seal was developed which is easy to mold and finish, and has excellent wear resistance. Though composed simply of iron and carbon, this metal is made highly ductile using an improved sintering procedure, so that it can be cold-rolled to precise configurations required.

Furthermore, this material contains aggregate cementite and free graphite in the pearlite matrix as shown in Photo 1 with consequent benefits of anti-wear and self-lubricating properties.

![Photo 1 The microstructure of sintered metal for side seal](image)

**OIL SEAL**

Fig. 16 shows a cross section of the oil seal. It is always in the presence of oil film that the oil seal is in contact with the side housing wall, which therefore is free from abnormal wear such as adhesion and scuffing. However, as travel distance is accumulated and oil seal lip wear progresses, the bearing width of the tapered lip becomes larger, causing its contact pressure to drop with reduced oil scraping function. This makes it essential to
minimize the lip wear.

The oil seal, as shown in Fig. 16 is given hard chrome plating on its inside circumference so that the chrome plating will always be in contact with the side housing wall. The base material of oil seal is the same wear-resistant cast iron as is used in the CE.

FRICITION AND WEAR CHARACTERISTICS OF SIDE HOUSING

Fig. 17 shows the friction characteristics of the oil seal lip sliding on the side housing, indicating markedly reduced friction force with the softnitrided side housing relative to the bare cast iron one.

The upper diagram of Fig. 17 indicates a considerable difference in the roughness of the side housing sliding face between the softnitrided side housing and the non-treated one.

Durability testing under an accelerating/decelerating mode, as shown in Fig. 18, indicates that the softnitriding of the side housing has the effect of greatly reducing wear of the sealing elements.

SEALING RUBBER

To maintain a precision axial clearance for the apex seal, a highly elastic sealing rubber instead of gasket is used on the surface between rotor housing and side housing. As shown in the upper portion of Fig. 19, two sealing rubbers, inner and outer are in use to prevent leakage of gas and coolant. The inner sealing rubber, located close to the combustion chamber, is made of highly heat-resistant silicone rubber with a fluorocarbon polymer sheet bonded on both sides of it to protect against combustion gas as shown in the lower portion of Fig. 19.

The outer sealing rubber is of ethylene propylene terpolymer (EPT) since the heat-resistance requirement is not as demanding as in the inner sealing rubber. Both inner and outer sealing rubber are capable of withstanding, under compressive condition, extended contact with hot coolant, resulting in minimized compressive permanent set.
SUMMARY

A number of new technologies were applied to material formulation and processing for essential components of the RE. Notable among those technologies and products developed are the high-strength rigidity aluminum alloy for the rotor housing, chrome plating the trochoid, heat-treating the side housing, hardening the apex seal by electron beam, sintering the side seal, and chrome-plating the oil seal inner face. All these derive the benefits of materials, thus adding new values to them and contributing much to the upgraded reliability and durability of the RE.

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REFERENCES

1. T. Muroki, Recent Technology Development of High-Powered Rotary Engine at Mazda. SAE-paper 841017.