

Construction of Model to Predict Wear Amount on Exhaust Valve Seats for Gasoline Engines

Yoshikatsu SHIWA*

Satoshi KISHIWADA*

Kenta YOSHII*

Noriyuki SATOU*

Keisuke ISHII*

Hisashi HASHIMOTO*

Takeshi FUJII*

Seisuke TAKAKI**

Hiroshi OSHIGE**

ABSTRACT

A technique has been created to predict the amount of wear on exhaust valve seats for gasoline engines. Through bench and rig wear tests, a prediction model was constructed with multiple factors as variables. Through these tests, the controllable factors were categorized, and sensitivity for each factor was determined from the measured wear data. The model was also applied to valve seats of different materials, confirming its versatility. By using the model to predict the amount of wear on valve seats in the cylinder head design phase, a cylinder head structure was quickly devised to increase valve seat wear resistance, shortening the development period and reducing development cost.

1. Introduction

In addition to the demands for greater performances, higher output, and a better fuel economy, today's automotive engines also face a demand for reduced CO₂ emissions to lower their environmental impacts. In response to this demand, Honda has been developing downsizing turbocharged engines⁽¹⁾. In turbocharged engines, gas is combusted at higher temperatures and pressures than in naturally aspirated engines. Thus, great attention should be given to wear on the valve seats, a factor which greatly affects engine performance.

Valve seats come in contact with intake and exhaust valves during the compression stroke, and they should be airtight to seal the compressed air-fuel mixture and the gas in the combustion stroke. Worn valve seat will reduce sealing performance with the valves, in turn degrading airtightness. The intake valve seats for gasoline engines are cooled by latent heat from vaporization during the intake stroke. Meanwhile, the exhaust valve seats are exposed to hot, high-pressured exhaust gases during the exhaust stroke, making them hotter than the intake valve seats. Thus, valve seat wear for gasoline engines is greater and needs more attention on the exhaust valve seats than on the intake valve seats⁽²⁾. To date, new materials have been developed to increase wear resistance for individual valve

seats⁽³⁾⁻⁽⁶⁾. However, as actual engine conditions for valve seats cannot be reproduced in stand-alone testing, valve seat wear resistance for actual engines should be confirmed with bench tests or road tests. If the tests show wear resistance to be low, the cylinder head structure should be redesigned and retested, in turn extending the development period and raising development costs. If the cylinder head structure is to be altered to increase valve seat wear resistance at the initial design phase, the amount of wear should first be predicted with testing. To date, however, valve seat wear has not been able to be predicted. The factor sensitivity to the numerous factors generating valve seat wear in testing could not be determined, and so no mathematical model has been constructed to predict wear.

Thus, in this research, the factor sensitivity for valve seat wear was determined for various tests, and a model was constructed to predict wear for exhaust valve seats in gasoline engines. The findings are as reported below.

2. Research Goals and Model Construction

The goal for the research was to build a model for predicting exhaust valve seat wear in bench test and road test for gasoline engines. The model was built by testing valve seat wear, and then using the response surface methodology from the wear data obtained in testing.

* Automobile R&D Center

** Nippon Piston Ring Co., Ltd.

Response surface methodology is a technique which uses test data to construct mathematical and statistical models to derive the optimum solution for the target variable(s). It is suited to constructing models from limited sets of test data. The factors resulting in valve seat wear are input into the model as variables to predict the amount of valve seat wear. The following steps were taken to build the model:

- Step 1: Identify wear factors for valve seats and sort by test
- Step 2: Construct a model for the air-fuel ratio, surface pressure on the valve seat face, and surface temperature on the valve seat face
- Step 3: Reflect deformation of the valve seat face into the model
- Step 4: Reflect combustion pressure and temperature into the model
- Step 5: Verify model accuracy and examine model versatility

3. Identifying Wear Factors for Valve Seats and Sorting by Test

A diagram of the main causes and factors in valve seat wear is shown in Fig. 1. There are 2 main causes in valve seat wear on actual engines: frictional force and the relative slip between the valve and valve seat. When a valve closes, it is impacted by the valve spring and seated on the valve seat. Then, the valve is pressed against the valve seat by combustion pressure, generating frictional force and causing the valve face to slip slightly. As the valve seat is also deformed by the combustion temperature and pressure, it makes non-uniform contact with the valve, generating a non-uniform frictional force. This generates various other phenomena⁽³⁾ as well, such as an adhesion of combustion products due to the change in air-fuel ratio, and change in friction coefficient and adhesion resistance due to the change in surface temperature on the valve seat face. The identified factors are:

Factor 1: Air-fuel ratio

Factor 2: Surface pressure on the valve seat face

Factor 3: Surface temperature on the valve seat face

Factor 4: Deformation of the valve seat face

Factor 5: Combustion pressure

Factor 6: Combustion temperature

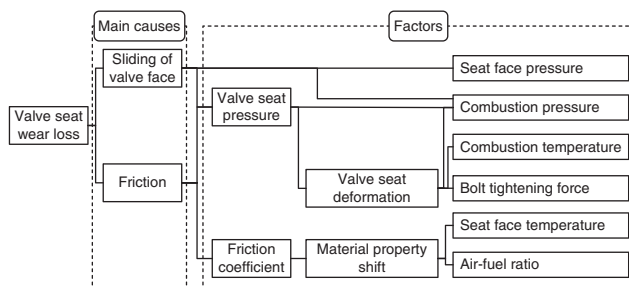


Fig. 1 Factor system diagram

Based on the identified factors, the authors proceeded to measure the amount of valve seat wear and construct a model, controlling for air-fuel ratio, and surface pressure, surface temperature, and the deformation of the valve seat face for the rig tests, as well as for combustion pressure and temperature for bench tests.

4. Constructing a Model for the Air-fuel Ratio, Valve Seat Face Pressure, and Valve Seat Face Temperature

4.1. Overview of Test Rig

The test rig used in testing is shown in Fig. 2. To get closer to an actual engine for the bench tests, the test rig was built with the following parts: actual engine valves, actual engine valve seats of ferrous sintered alloy comprising Cr-Mo-Co hard particles, and a setting plate fabricated from the cylinder head material used in the actual engine.

Various test conditions were adjusted. The valve seat face pressure with the valve seated was adjusted through valve lift with the cam mechanism. The air-fuel ratio was also adjusted through a mixture of LP gas and air, supplied to a burner. Finally, valve seat face temperature was adjusted by changing the height of the burner.

4.2. Determining Factor Sensitivity

The rig tests were performed within the driving condition range of bench tests to measure the amount of valve seat wear. An L18 orthogonal table of the test conditions is given in Table 1. The factorial effects from the L18 test results are given in Fig. 3. From the factorial effects, sensitivity was determined to be highest for valve seat face temperature. Meanwhile, sensitivity for the air-fuel ratio was determined to be the same as that for valve seat face pressure.

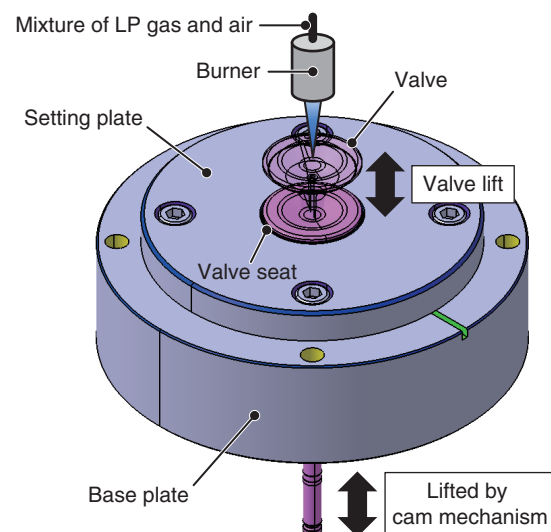


Fig. 2 Valve seat testing machine

Table 1 L18 orthogonal table

No.	Air-fuel ratio [-]	Seat face pressure [MPa]	Seat face temperature [deg C]	Cam rotation speed [r/min]	Valve rotation speed [r/min]	Test duration time [hour]
1	11.9	12.1	240	3000	20	6
2	11.9	10.1	240			
3	10.7	12.1	280			
4	10.7	10.1	280			
5	13.1	8.1	200			
6	13.1	8.1	280			
7	14.3	10.1	200			
8	14.3	8.1	200			
9	14.3	12.1	240			
10	13.1	12.1	240			
11	11.9	8.1	280			
12	11.9	12.1	320			
13	13.1	10.1	200			
14	13.1	10.1	280			
15	14.3	10.1	240			
16	14.3	12.1	320			
17	14.3	12.1	200			
18	10.7	12.1	200			

4.3. Constructing the Model

Using the valve seat wear measurements from the L18 tests, a model was constructed with valve seat face pressure and temperature and air-fuel ratio as the input parameters.

For the response surface methodology, a radial basis function network (RBF network)⁽⁷⁾ was used given as they are more compatible with objective function distributions than polynomial models over the entire design space. RBF networks approximate the objective function distribution as a summation of basis functions. The RBF network approximated objective function $f(x)$ as given in Eq. (1), using distance $\|x - x_i\|$ from measuring point i , radial basis function $\phi(r)$, coefficient a_i , and scaling parameter c .

$$f(x) = \sum_{i=1}^N a_i \phi\left(\frac{\|x - x_i\|}{c}\right) \quad (1)$$

Hardy Multiquadric Eq. (2) was used as the basis function:

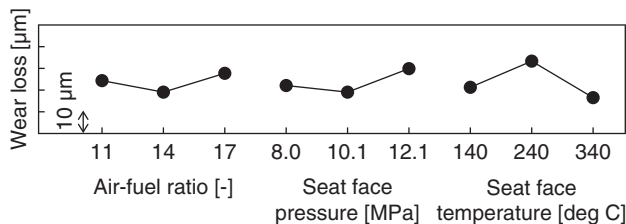


Fig. 3 Factorial effects on L18 test

$$\phi(r) = (1 + r^2)^{1/2} \quad (2)$$

The IDAJ optimization tool modeFRONTIER[®] was used to create the model. Valve seat wear W_0 can be expressed with the model given by Eq. (3):

$$W_0 = f(AF, P_s, T_s) \quad (3)$$

In Eq. (3), AF is the air-fuel ratio, P_s is the seat face pressure, and T_s is the seat face temperature.

4.4. Verifying Accuracy of Model Predictions

Prediction accuracy using the constructed model was verified by entering the rig test conditions (air-fuel ratio, valve seat face pressure and temperature) into the model and comparing the predicted valve seat wear to the test results. The compared results are given in Fig. 4. The constructed model was able to predict valve seat wear at a high accuracy of $R^2 = 1.00$.

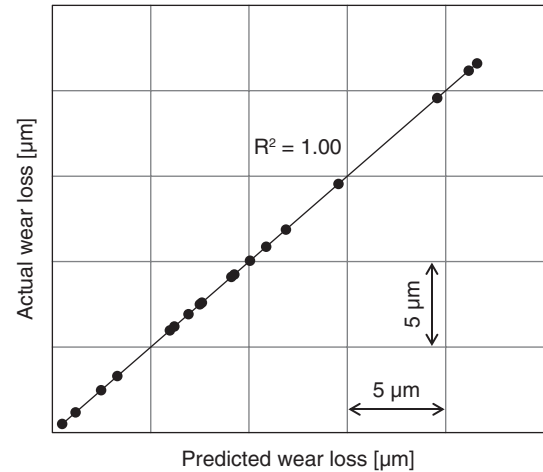


Fig. 4 Comparison between predicted wear loss and actual wear loss

5. Reflecting Valve Seat Face Deformation into the Model

5.1. Test Overview and Measuring Method for Valve Seat Face Deformation

The test rig was the same as that shown in Fig. 2. The methodology for valve seat face deformation is illustrated in Fig. 5. Valve seat face deformation, equivalent to that in the actual engine, was recreated by pinching shim plates between the setting plate and base plate, then forcing deformation of the setting plate. The valve seat was measured before testing with a three-dimensional measuring machine, confirming deformation to be equivalent to that in an actual engine. Specifications for the three-dimensional measuring machine used in measurement are given in Table 2, and the appearance of the measured valve seat

Table 2 Measuring machine specifications

Manufacturer		TOKYO SEIMITSU ACCRETECH
Product name		SVA Fusion
Accuracy	MPE _E	1.9 + 4 L/1000 μm
	MPE _p	1.9 μm
	MPE _{THP}	2.8 μm

is shown in Fig. 6. Deformation was measured with the following steps:

Step 1: Press fit the valve seats into the setting plate

Step 2: Form a contact surface with the valves

Step 3: Measure the contact surface after forming

Step 4: Pinch the shim plates and tighten the plates

Step 5: Measure the contact surface after tightening

Thus, valve seat face deformation was calculated based on these steps by superimposing measurements from after forming (Step 3) and measurements from after tightening (Step 5) to compare the data. A sample calculation is given in Fig. 7. The data was compared in the valve lift axial direction; results were taken as positive when the measuring plane, after tightening, was displaced in the valve lift direction, and negative when displaced in the opposite direction.

Figure 8 shows three-dimensional measurements of the valve seat face deformation as reproduced in this test and valve seat face deformation results from an actual engine as calculated with computer-aided engineering (CAE). The CAE results are calculated with the cylinder heads attached in ambient temperature. The three-dimensional measurements show similar amplitude and cycle of valve seat face deformation as the CAE results, meaning that this approach reproduced valve seat face deformation equivalent to that in actual engines. Hereinafter, the amplitude of

deformation for the valve seat will be treated as valve seat face deformation.

5.2. Test Conditions and Determining Sensitivity

In this test, wear was measured when a valve seat was deformed and when none were deformed, taking air-fuel ratio, valve seat face pressure, and valve seat face temperature as constant. The measurement results are given in Fig. 9. Under the same conditions, wear increased by deforming the valve seats, indicating sensitivity to wear.

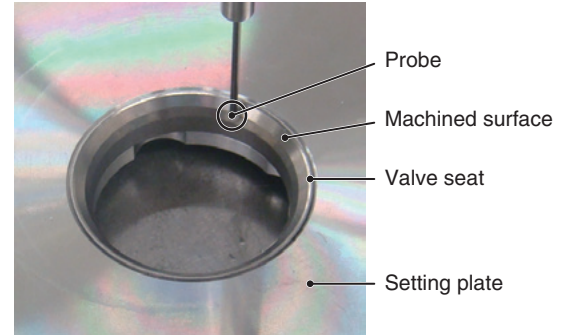


Fig. 6 Appearance of measured valve seat

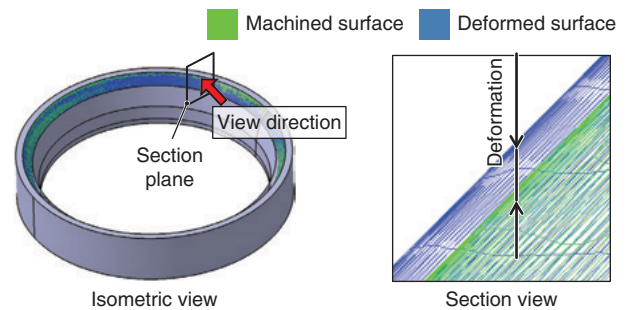


Fig. 7 Calculations for valve seat face deformation

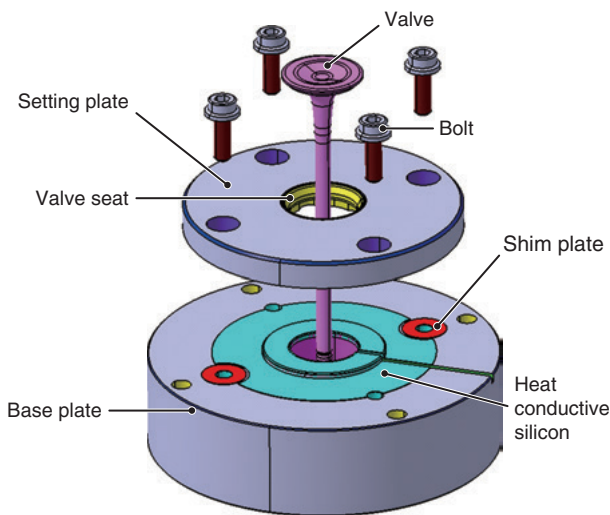


Fig. 5 Methodology of valve seat face deformation

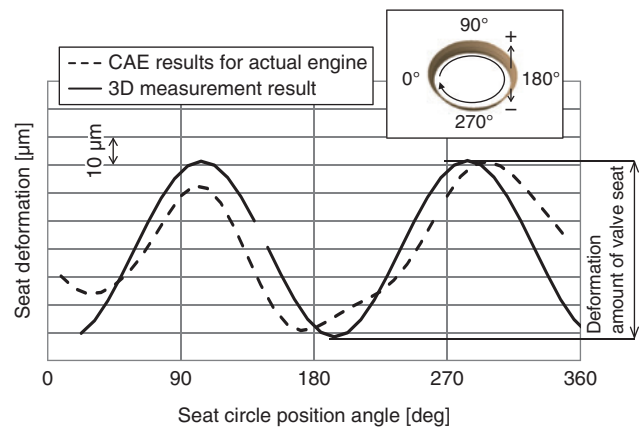


Fig. 8 Valve seat face deformation

5.3. Reflecting into the Model

Valve seat face deformation is reflected into the model. Inputting the air-fuel ratio, valve seat face pressure, and valve seat face temperature, wear W_ε for this test was predicted from predicted wear W_0 , valve seat face deformation $\Delta\varepsilon$, and coefficient B using Eq. (4).

$$W_\varepsilon = (B * \Delta\varepsilon + 1) W_0 \quad (4)$$

The wear prediction model was constructed by inputting air-fuel ratio, valve seat face pressure, valve seat face temperature, and valve seat face deformation as the parameters for Eq. (4).

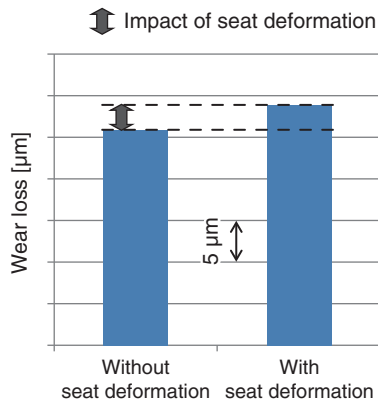


Fig. 9 Impact of seat wear loss on seat deformation

6. Reflecting Combustion Pressure and Temperature into the Model

6.1. Bench Test Conditions and Wear Measurements

The engine specifications used for this test are shown in Table 3. Valve seat wear was measured using radiation wear measurement. Radiation wear measurement is a method of measuring valve seat wear by activating the valve seat to be measured and then measuring the radiological dosage emitted by the valve seat⁽⁸⁾. An image of the radiation detection machine is given in Fig. 10, and the engine bench test conditions are given in Table 4.

6.2. Reflecting Test Results into the Response Surface Model

The change in wear loss ratio with change in combustion pressure is shown in Fig. 11. Wear loss ratio increases with combustion pressure. Combustion temperature also rises with combustion pressure. This wear loss ratio increase was attributed to a valve micro slip due to the increase in combustion pressure and temperature.

Based on this attribution, valve seat face pressure due to valve micro slip from combustion pressure and temperature was calculated with CAE and reflected into the model to compensate for combustion pressure and temperature.

Table 3 Engine specifications

Type of engine	L4 DOHC i-VTEC Turbo	
Bore × Stroke (mm)	86.0 × 85.9	
Displacement (cm ³)	1996	
Compression ratio	9.8	
Number of valves	Intake	2
	Exhaust	2
Valve head dia./Stem dia. (mm)	Intake	35.0/34.5
	Exhaust	29.0/28.5
Valve seat width (mm)	1.6	
Valve seat base hard particles	Cr-Mo-Co hard particles	
Maximum power (kW/rpm)	228/6500	
Maximum torque (Nm/rpm)	400/2500-4000	
Fuel type	Petrol	

Table 4 Engine bench test conditions

No.	Engine speed [r/min]	Intake air pressure [hPa]	Engine power [kW]	Test duration time [hour]
1	2750	750	27	116.3
2	4500	2300	169	8.0
3	5700	1175	115	30.5
4	5700	1480	145	65.0
5	5700	1950	182	6.5
6	6500	1480	126	20.0

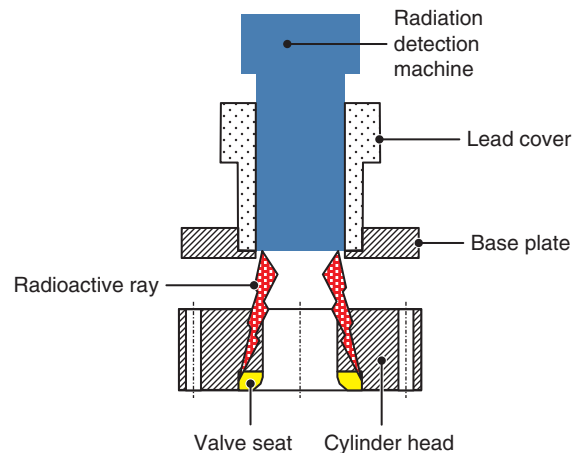


Fig. 10 Wear loss measured with radioactive rays

Equation (5) was derived to predict wear amount W_{total} for the test from valve seat wear W_e as predicted by the model accounting for valve seat face deformation, valve seat face pressure P_v due to valve micro slip, and coefficients D and E .

$$W_{total} = D \cdot \exp(E \cdot P_v) \cdot W_e \quad (5)$$

Thus, a model to account for combustion pressure and temperature during bench test was constructed from Eq. (5) by inputting the air-fuel ratio and the pressure, temperature, deformation, and pressure due to the valve micro slip of the valve seat face.

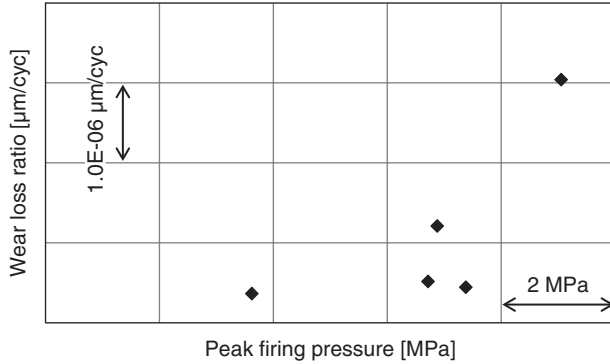


Fig. 11 Wear loss ratio and combustion pressure

7. Verifying Model Accuracy and Examining Model Versatility

7.1. Verifying Model Accuracy

Valve seat wear as predicted with the model for bench test and road endurance test are given in Fig. 12. The model was able to predict valve seat wear for bench test and road endurance test at a high accuracy of $R^2 = 0.9105$.

7.2. Examining Model Versatility

Model versatility was investigated based on application of the model when using a different valve seat material. The valve seat material considered was ferrous sintered alloy, comprising Cr-Co-Fe-Ni hard particles. This differs from a ferrous sintered alloy comprising Cr-Mo-Co hard particles. Model application and versatility when using the different valve seat material was investigated by taking the following steps:

- Step 1: Build a test rig as presented in Section 4.1., using the actual engine valves and valve seats
- Step 2: With the test rig from Step 1, select one of the test conditions from the L18 orthogonal table, given in Table 1 in Section 4.2. and measure valve seat wear
- Step 3: Using the test condition selected in Step 2, compare the valve seat wear as measured in Section 4.2. with that measured in Step 2, then calculate the wear correction value for the model
- Step 4: Correct the model using the wear correction value

calculated in Step 3

The model, as corrected by following these steps, was used to predict valve seat wear for bench test with the different valve seat material. The predictions are given in Fig. 13. The results accurately predicted valve seat wear in the bench test, meaning the model is highly versatile.

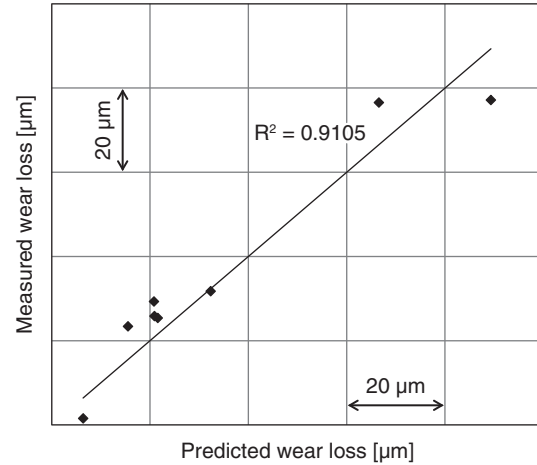


Fig. 12 Wear loss predicted with response surface model and actual road tests

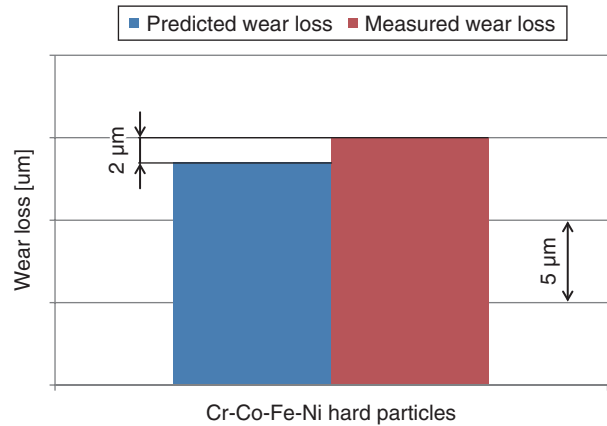


Fig. 13 Predicted results for engine with different materials

8. Conclusion

Through this research, the following findings were made and a model was successfully constructed for predicting exhaust valve seat wear in gasoline engines. By doing so, a method has been devised to reduce wear for various tests while building the cylinder head at the initial design phase of engine development to help increase valve seat wear resistance. This has reduced redesigns and retesting, in turn shortening the development period and reducing development costs.

- (1) By determining the factor sensitivity for wear, sensitivity was found to be highest for valve seat face temperature, making it a factor to keep note of.
- (2) Valve seat face deformation was found to be sensitive to wear.
- (3) By measuring valve seat wear for bench test using radiation wear measurement, it was determined that the wear loss ratio increases with combustion pressure.
- (4) Valve seat wear was also predicted when using different valve seat material, showing that the model constructed is highly versatile.

References

- (1) Nakano, K., Wada, Y., Jono, M., Narihiro, S.: New In-Line 4-Cylinder Gasoline Direct Injection Turbocharged Downsizing Engine, Honda R&D Technical Review, Vol. 28, No. 1, p. 139-146
- (2) Sato, K., Midorikawa, T., Yamasaki, Y., Takahashi, T.: Development of Valve Seat Material for Gas Fueled Engine, HONDA R&D Technical Review, Vol. 11, No. 1, p. 149-156
- (3) Oketani, H., Tsubota, R., Ishida, M.: Development of Low-cost Material for Engine Exhaust Valve Seat, Honda R&D Technical Review, Vol. 17, No. 1, p. 130-137
- (4) Kawata, H., Fujitsuka, H.: Co, Pb-Free Exhaust Valve Seat Insert Material, Hitachi Chemical Technical Report, No. 44, p. 31-34, (2005)
- (5) Ootani, T., Yahata, N., Fujiki, A., Ehira, A.: Impact Wear Characteristics of Valve and Valve Seat Insert Materials for Engines at High Temperature (Plane Impact of Martensitic Heat Resistant Steel SUH3 against Fe-Base Sintered Alloy), Transactions of the Japan Society of Mechanical Engineers Series C, Vol. 60, No. 576, p. 333-339, (1994) (in Japanese)
- (6) Ootani, T., Yahata, N., Hatano, Y., Maki, K.: Impact Wear Characteristics of Engine Valve and Valve Seat Insert Materials at High Temperature (2nd Report, Impact Wear Tests of Austenitic Heat Resistant Steel SUH36 against Two Types of Fe-Base Sintered Alloy with Plane and Oblique Surfaces), Transactions of the Japan Society of Mechanical Engineers Series C, Vol. 62, No. 598, p. 265-272, (1996) (in Japanese)
- (7) Kitayama, S., Sakai, S., Arakawa, M., Yamazaki, K.: Sequential Approximate Optimization Using Radial Basis Function Network (Application to the Discrete Design Variable Problems), Transactions of the Japan Society of Mechanical Engineers Series C, Vol. 78, No. 787, p. 177-190, (2012) (in Japanese)
- (8) Uemoto, R., Uno, H., Nagano, A., Oonishi, T., Kameda, D., Fukuda, N., Yanagisawa, Y., Yoshida, A., Kubo, T., Kambara, T.: Application of the real time wear measurement by using RI beam, JSAE Annual Congress Proceedings, No. 30-11, p. 9-11, (2011) (in Japanese)

■ Author ■



Yoshikatsu SHIWA



Satoshi KISHIWADA



Kenta YOSHII



Noriyuki SATOU



Keisuke ISHII



Hisashi HASHIMOTO



Takeshi FUJII



Seisuke TAKAKI



Hiroshi OSHIGE