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A Study on Wear and Wear Mechanism of Exhaust Valve and Seat Insert Depending on Different Speeds Using a Simulator

Jae Soo Hong, Keyoung Jin Chun*
Fusion Tech Center, Korea Institute of Industrial Technology,
35-3, HongChonRi, IbJangMyun, ChonAnSi, ChungNam 330-825, Korea
Young Han Youn
School of Mechatronics Engneering, Korea University of Technology and Education,
307, GaChunRi, ByungChonMyun, ChonAnSi, ChungNam 330-708, Korea

The wear of engine valve and seat insert is one of the most important factors which affect engine performance. Because of higher demands on performance and the increasing use of alternative fuel, engine valve and seat insert are challenged with greater wear problems than in the past. In order to solve the above problems, a simulator was developed to be able to generate and control high temperatures and various speeds during motion. The wear simulator is considered to be a valid simulation of the engine valve and seat insert wear process with various speeds during engine activity. This work focuses on the different degrees of wear at three different singular test speeds (10 Hz, 25 Hz & multi-Hz). For this study, the temperature of the outer surface of the seat insert was controlled at 350℃, and the test load was 1960 N. The test cycle number was 6.0×10^6. The mean (±standard error) wear depth of the valve at 10 Hz and 25 Hz was 45.1 (±3.7) μm and 81.7 (±2.5) μm, respectively. The mean wear depth of the seat insert at 10 Hz and 25 Hz was 52.7 (±3.9) μm and 91.2 (±2.7) μm, respectively. In the case of multi-Hz it was 70.7 (±2.4) μm and 77.4 (±3.8) μm, respectively. It was found that higher speed (25 Hz) cause a greater degree of wear than lower speed (10 Hz) under identical test condition (temperature, valve displacement, cycle number and test load). In the wear mechanisms of valves, adhesive wear, shear strain and abrasive wear could be observed. Also, in the wear mechanisms of seat inserts, adhesive wear, surface fatigue wear and abrasive wear could be observed.

Key Words : Engine Valve, Seat Insert, Wear, Simulator, Speed

1. Introduction

Engine valve and seat insert wear is one of the most important factors which affect engine performance. Because of higher demands on performance and the increasuring use of alternative fuel, engine valve and seat insert are challenged with greater wear problems than in the past. Such needs require strict control on the wear of the valve and seat insert, which are major components of any vehicle engine. The valve collides with and slides in the seat insert at high temperatures by means of the action of the valve spring (Ootani et al., 1995). Occasionally, friction between the valve and seat insert is accompanied by sliding. Certain phenomena of the valve and seat insert wear can be observed depending on the engine operation

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* Corresponding Author,
E-mail : chun@kitech.re.kr
TEL : +82-41-589-8430; **FAX** : +82-41-589-8413
Fusion Tech Center, Korea Institute of Industrial Technology, 35-3, HongChonRi, IbJangMyun, ChonAnSi, ChungNam 330-825, Korea. (Manuscript **Received** February 3, 2006; **Revised** August 31, 2006)

status. These include internal temperature, power output, speed or RPM (revolutions per minute) etc. Because their wear rates are not well clarified quantitatively at present, it is difficult to understand the wear mechanisms of the valve and seat insert. There have been a few reported studies on their wear mechanisms so far (Sato et al., 2000 ; Scott et al., 1995). Among them there has been no analysis of the wear rate and wear mechanism due to speed (RPM) change. A great amount of research throughout numerous studies has taken place concerning the valve and seat insert (Fujiki et al., 1992 ; Kim et al., 1999 ; Pyle et al., 1993). However, the majority of such inquiries have only taken factors into consideration at a constant RPM while the actual condition for driving vehicles has fluctuation in the operational RPM. As such, it is difficult to examine the wear rate and the wear mechanism of the valve and seat insert depending on the engine RPM.

The objectives of this study focus on the wear rate and the wear mechanism of an exhaust valve and seat insert depending on different speeds.

2. Test Device (simulator)

Dynamometer engine testing is often employed to investigate valve and seat insert wear problems. This is very expensive and time consuming test, and does not help in finding valve and seat insert wear case only. In other words, this result includes many other parts' problems in the engine. In order to identify the critical parameters leading to valve and seat insert recession, it is necessary to analyze the valve and seat insert wear mechanisms in detail (Lewis et al., 1999).

In order to examine the wear rate and the wear mechanism of the valve and seat insert (Zhao et al., 1997 ; Dissel et al., 1989), this study has applied a simulator that is exclusively used for valve and seat insert wear. This simulator takes into account such aspects as speed change, temperature, load and friction between the valve and seat insert, etc. (Chun et al., 2004), that represent the internal conditions of an actual vehicle engine.

The simulator exclusively used for this study has been designed to be similar to an internal combustion engine. It consists of three components : a hydraulic power unit, a control unit and a mechanical unit (see Figure 1).

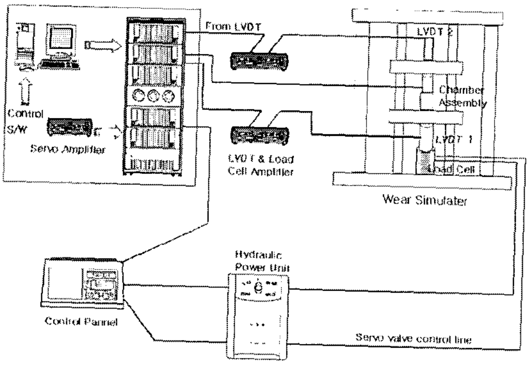
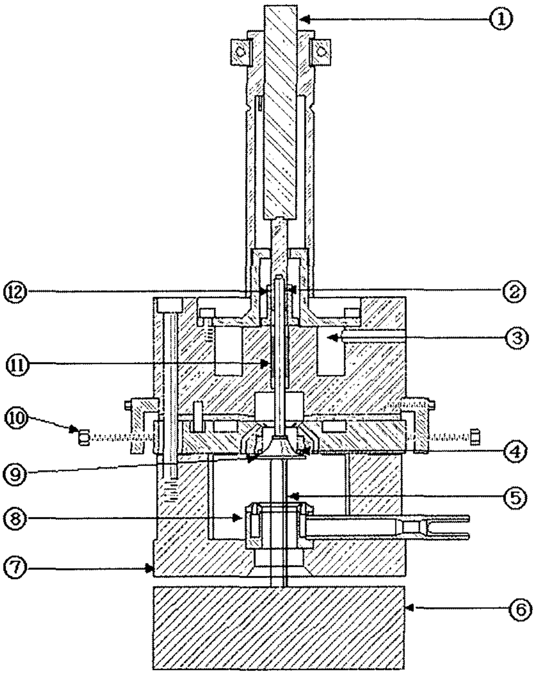


Fig. 1 Schematic of valve and seat insert wear simulator

The hydraulic unit simulates the combustion pressure of the engine to regulate the wear simulator pressure and transmit force to the valve head. This force can be regulated up to 4000 kgf. The control unit consists of the following. ① Pentium Ⅲ Computer (RAM 128M b), ② AD Board (100 KW, 12 bits, SE16), ③ DA Board (2 ch, 12 bits), ④ Waveform Generation Board (Saw, Sine, Square), ⑤ Servo Amplifier, ⑥ LVDT & Load Cell Amplifier and ⑦ Thermocouples. The control unit monitors and controls all of the test parameters such as the force imposed on the valve head, seat insert temperature, distance between the valve and seat insert, frequency of fluctuation and test period.

The internal temperature of the chamber is monitored by five thermocouples. Three thermocouples are located 120° apart along the outer surface of the seat insert. The remaining two thermocouples are used to monitor the cooling system. In order to constantly maintain the desired internal temperature, cooling channels have been installed, which can control the temperature up to 900℃. In addition, two sets of LVDTs (Linear Variable Differential Transformer), LVDT1 and LVDT2, have been installed, one on the lower part of the piston and the other on the upper part of the valve stem. These help to maintain the desired distance between the valve and the seat insert. The range of the LVDT movement is +/−50 mm (see Figure 2).



① LVDT ② Return Spring ③ Cooling Channels (water)
④ Seat Insert ⑤ Push Rod
⑥ Hydraulic Actuator (piston) and Load Cell
⑦ Heat Chamber ⑧ Burner Assembly ⑨ Valve
⑩ Adjusting Offset Screw ⑪ Guide ⑫ Guide Bush

Fig. 2 Schematic of chamber assembly

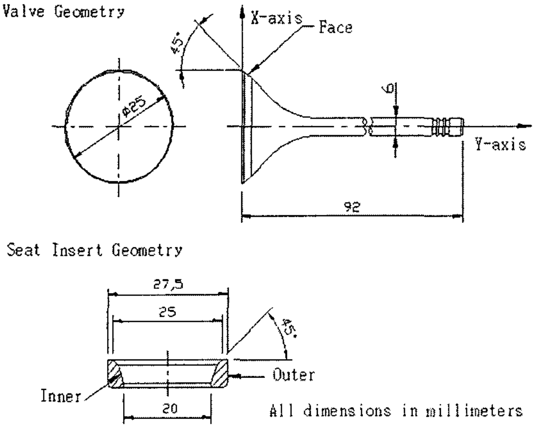


Fig. 3 Valve and seat insert geometry

3. Test Method

The exhaust valves and seat inserts, currently used for an existing vehicle, were used as specimens (see Figure 3). The valve material consists of STR35, a valve steel, and the seat insert material consists of HVS1-2, a sintered iron alloy. Table 1 shows the chemical composition of each material.

The hardness of each specimen was measured after having been ground using a Vickers hardness tester. The hardness test was carried out five times. Average hardness was obtained from the measured values excluding the maximum and minimum ones. The hardness obtained in this manner was 419 (Hv 500 g) for the valve and 397.7 (Hv 500 g) for the seat insert.

The surface roughness (Ra) of the valve and seat insert was 0.45 μm and 0.41 μm, respectively.

Wear tests were performed for three speeds, 10 Hz, 25 Hz and multi-Hz (10 Hz-25 Hz) (see Figure. 4). To achieve objectivity and consistency, the tests were performed for six specimens per speed under identical test conditions. As fuel, LPG, known as the most erosive fuel for engines, was used for convenience and also for creating the severest possible wear environment in the chamber. The applied test temperature was 350℃ at the outer surface of the seat insert (760℃ at valve face). The valve was opened and closed 6.0×10^6 times, and the test load was 1960 N (see Table 2).

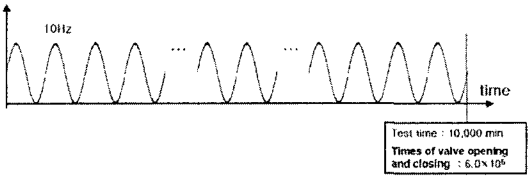
Wear depth was measured by observing a surface of specimen before and after the test using a confocal laser microscope (Model OLS 1100 made by Olympus, Resolution 0.01 μm). Then, the measured values before and after the test were analyzed and compared. In addition, using a SEM (Model JSM 6400JEOL made by JEOL, Resolution 4 nm),

Table 1 Chemical compositions (wt.%)

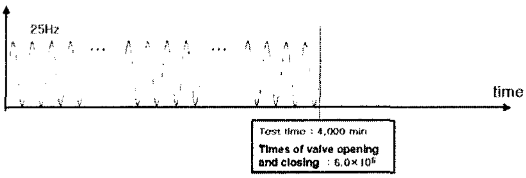
Material	C	Si	Mn	Cr	Mo	Ni	Cu	Fe
Valve (STR35)	0.53	0.31	9.00	21.00	—	3.87	—	Bal
Seat Insert (HVS1-2)	1.1	—	—	7.5	2.0	2.0	15	Bal

Table 2 Wear test conditions

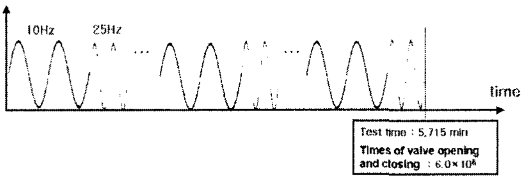
Hz	10	25	Multi-Hz (10-25)
Test temperature at the outer surface of the seat insert (℃)	350		
Valve displacement (mm)	1.0		
Number of times valve was opened and closed	6.0×10^6		
Test load (N)	1960		
Fuel used	LPG		



(a) 10 Hz cyclic test



(b) 25 Hz cyclic test



(c) 10 Hz-25 Hz (Multi-Hz) cyclic test

Fig. 4 Type of cyclic test

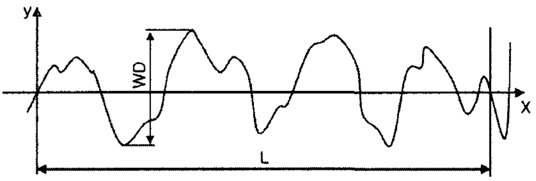


Fig. 5 Measurement of wear depth

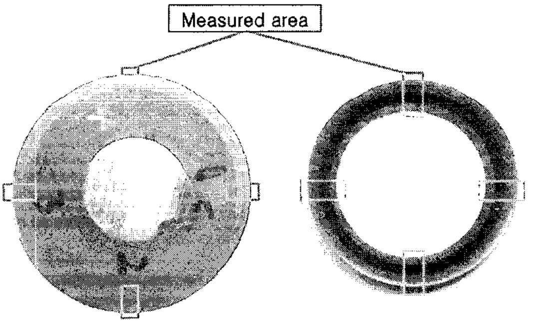


Fig. 6 Measured area of a valve and seat insert

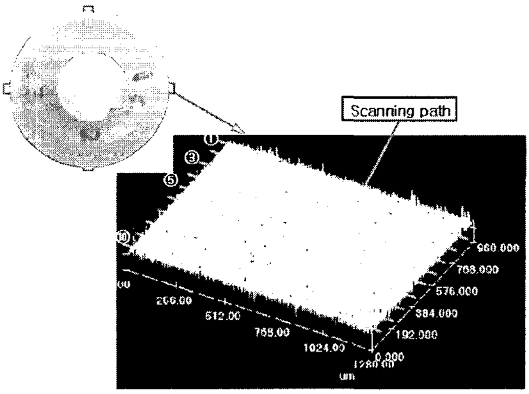


Fig. 7 Scanning path of the wear face

the valve face and seat insert surfaces were observed before and after the test to examine the wear mechanism.

4. Test Result

4.1 Wear depth

Figure 5 shows how to measure the wear depth of the valve and seat insert. Here, the wear depth (WD) refers to the difference between the highest and the lowest amount with the length (L) to be measured. In this figure, y-axis refers to the same direction of the valve stem. The definition of wear depth adopted here was not a precise measure of the amount of material removal, but it provided a satisfactory ranking measure.

To guarantee the reliability of the measurements and minimize differences of the wear depth caused by eccentricity, the measured area was divided 90° apart along the surface of the valve and seat insert (see Figure 6).

Each measured area was scanned 10 times (see Figure 7), and the scanned datas were averaged for the wear depth of the each measured area.

Figure 8 shows one example of the three-dimensional wear scar profile at the maximum contact area of a seat insert at 25 Hz, which was measured using the OLS1100.

Figure 9 and Table 3 illustrate the wear depth of the valve and the seat insert for each speed (Hz) with statistical data. The mean (±Standard Error) wear depth of the valve and seat insert at 10 Hz was 45.1 (±3.7) μm and 52.7 (±3.9) μm, respectively. The mean (±Standard Error) wear depth of the valve and seat insert at 25 Hz was 81.7 (±2.5) μm and 91.2 (±2.7) μm, respectively. In the case of multi-Hz it was 70.7 (±2.4) μm and 77.4 (±3.8) μm, respectively.

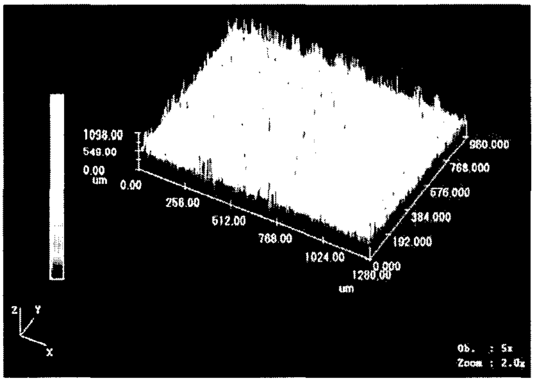
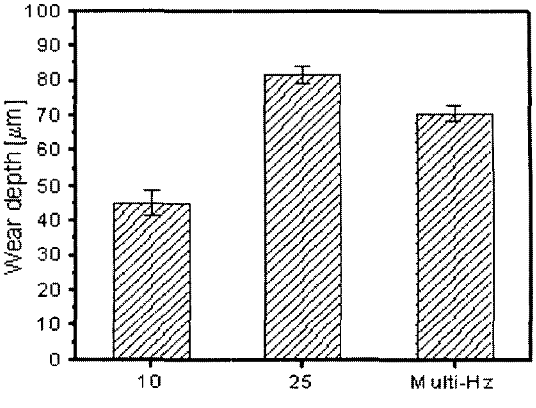
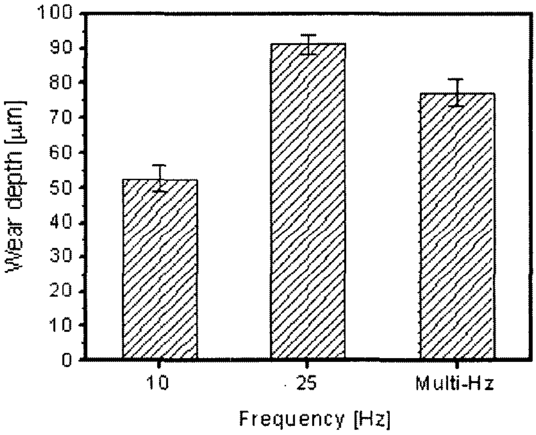


Fig. 8 Three-dimensional wear scar profile at the maximum contact area of a seat insert at 25 Hz, which was measured using the OLS1100



(a) Valve



(b) Seat Insert

Fig. 9 Histograms show the means for wear depth of worn valves and seat inserts. Error bars indicate standard error of the mean

Table 3 Wear depth of worn valve and seat insert

(μm)

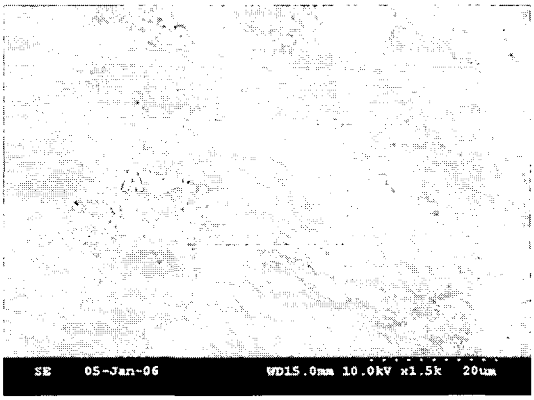
10Hz	Specimen No.	1	2	3	4	5	6	Mean±SE
	Valve	43.9	49.1	41.5	50.3	43.1	42.8	45.1±3.7
	Seat Insert	51.4	57.2	48.4	57.9	51.3	50.2	52.7±3.9
25Hz	Specimen No.	1	2	3	4	5	6	Mean±SE
	Valve	79.4	85.5	82.3	81.7	82.6	78.4	81.7±2.5
	Seat Insert	88.5	92.7	93.8	87.1	91.5	93.3	91.2±2.7
Multi-Hz	Specimen No.	1	2	3	4	5	6	Mean±SE
	Valve	73.1	70.8	68.9	73.9	67.9	69.4	70.7±2.4
	Seat Insert	81.5	72.6	79.4	81.1	73.9	75.8	77.4±3.8

As can be seen from the measured values in Figure 9, wear depth increases as the speed (Hz) increases. Here, since an increase in the Hz signifies an increase in the RPM of the vehicle engine, a severe increase in RPM may be responsible for such drastic increase in the valve and seat insert wear.

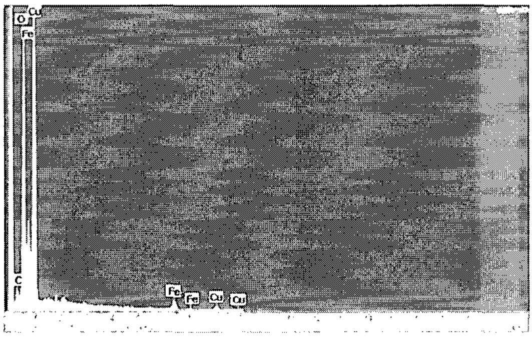
4.2 Wear mechanism

4.2.1 Adhesive wear

Adhesive wear occurs when the valve and seat insert are in sliding contact, during which process fragments are detached from one surface and either attach back onto the original surface or attach to another surface. Some of them fall off and don't reattach.



(a) FE-SEM microscope of worn valve seating face



(b) EDS result of point A

Fig. 10 SEM micrograph of a worn valve surface at 10 Hz showing adhesive wear (Temperature=350℃ ; Test load=1960 N), Magnification 1500×

During sliding, fragments from one surface contact fragments from the other surface. When such contact does not take place, fragmentation may not occur at the interface. As a result, movable fragments will be generated. The roughness of each surface has substantial impact on the adhesive wear. Figure 10 shows the typical adhesive wear on a valve, which was analyzed by the SEM and EDS. Transferred material Cu from the seat insert, which is shown in Table 1, was found in the adhesive surface of the valve by the EDS result.

Figure 11 is the SEM photograph of the typical adhesive wear on a seat insert.

4.2.2 Shear strain

The shear strain affecting the surface wear may be considered as a characteristic of the plastic deformation process of the material surface. The result of shear strain exceeding the limit of the plastic deformation of the material surface can be classified as wear. It can be observed that in the case of the valve and seat insert, the typical appearance of the shear strain generated due to wear is identical to the flow in the ridge or radial direction. Shear strain accompanies fatigue fracture due to repeated impact and sliding on the face.

Figure 12 provides an illustration of typical shear strain by sliding, which was analyzed by the SEM.

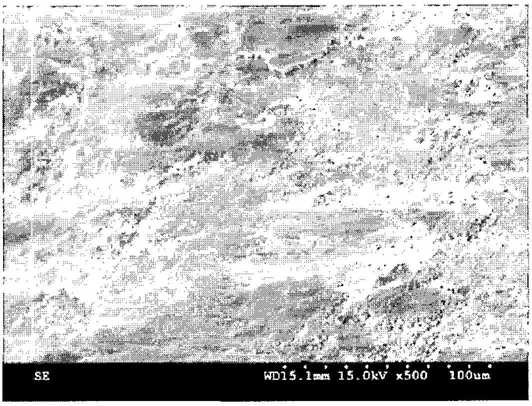


Fig. 11 SEM micrograph of a worn seat insert surface at 10 Hz showing adhesive wear (Temperature=350℃ ; Test load=1960 N), Magnification 500×

4.2.3 Surface fatigue wear

The loading and unloading cycles that expose the material cause a crack to form on or below the material surface, creating a large fragment or damaging the surface leaving large holes in its end. The form of wear similar to this type of surface fatigue wear can be seen from a brittle material that breaks into large fragments. Upon repeated sliding or rotation of surfaces, surface fatigue wear is frequently noticed from the seat insert as it sinters from the iron powder. Figs. 13 (a) ~ (d) in Figure 13 illustrate the surface fatigue wear process, which is one of the wear mechanisms occurring due to the repeated friction between the valve and seat insert. Figure 13(a) shows a surface where two different areas coexist: an area where wear is about to occur and another area where wear has not yet occurred. Figures 13 (b) and (c) depict the surfaces immediately prior to the occurrence of wear at high temperatures.

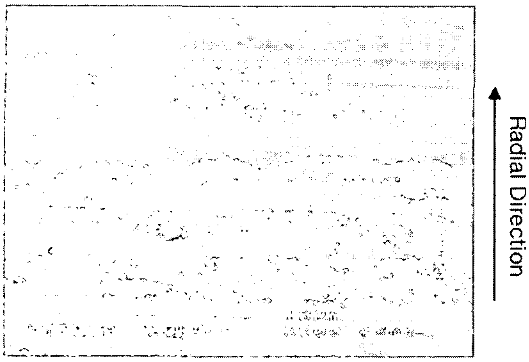


Fig. 12 SEM micrograph of a worn valve surface at 10 Hz showing shear strain by sliding (Temperature=350℃ ; Test load=1960 N), Magnification 500×

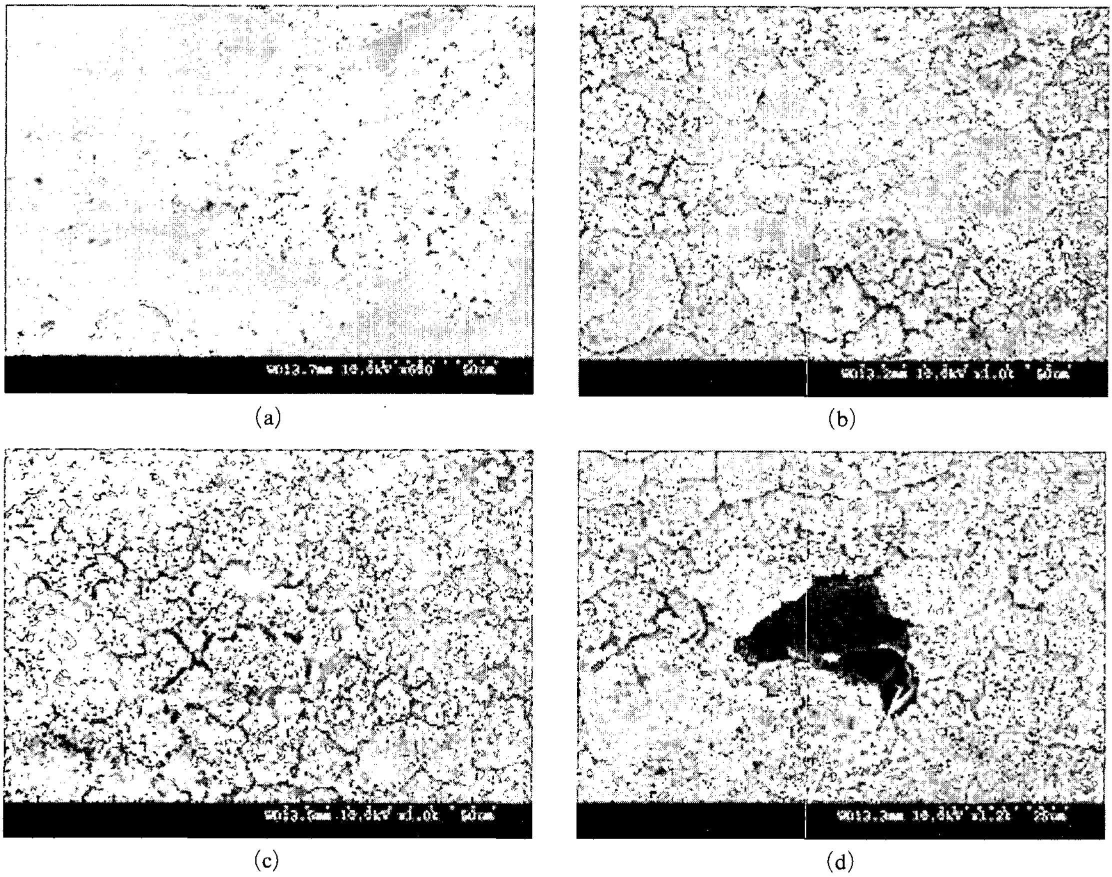

(a) (b) (c) (d)

Fig. 13 SEM micrographs of a worn seat insert surface at 25 Hz showing surface fatigue wear (Temperature=350℃ ; Test load=1960 N), Magnification 1200×

Figure 13(d) shows the surface damaged by the friction between two sliding bodies and shear strain at high temperatures.

5. Discussion and Conclusion

Wear of the valve and seat insert could have been observed in various ways depending on the engine operation status including internal temperature, mileage or cycle number, speed or RPM (Hz), kinds of fuel and kinds of valve and seat insert materials. However, the majority of previous studies simply take into consideration a constant speed (Hz) without taking into account the change in the operational RPM, which should be the condition for driving the actual vehicle. Among them there has been no analysis of the wear rate and the wear mechanism due to speed (Hz) changes. This study performed tests concerning the wear depth and wear mechanism of the valve and seat insert, under conditions similar to those of a vehicle engine, using a simulator which could change speed (Hz) during motion. In this study, tests have been conducted using three speeds (10 Hz, 25 Hz, Multi-Hz) for the wear depth and wear mechanism of the valve and seat insert by means of a wear simulator with the identical test conditions similar to those of an actual vehicle engine. The summary of the test results are as follows:

(1) The mean wear depth (±Standard Error) of the valve and seat insert at 10 Hz was 45.1 (±3.7) μm and 52.7 (±3.9) μm, respectively. In addition, the mean wear depth (±Standard Error) of the valve and seat insert at 25 Hz was 81.7 (±2.5) μm and 91.2 (±2.7) μm, respectively. Lastly, the mean wear depth (±Standard Error) of the valve and seat insert at multi-speeds (variable from 10 Hz to 25 Hz) was 70.7 (±2.4) μm and 77.4 (±3.8) μm, respectively. Therefore, it can be seen that the wear depth of the valve and seat insert increases sharply in accordance with a rise in the speed (Hz). According to these results, an increase in the engine revolution may cause the engine performance of a vehicle to decrease due to the rapid wear of the valve and seat insert.

(2) From the valve wear mechanism, the following phenomena were observed:

- At 10 Hz, the following types of wear were observed: adhesive wear causing sliding of the valve and seat insert due to friction between the valve and seat insert; and shear strain wear in a radial direction resulting in the breakdown of metal particles due to the plastic deformation in the material, or fragments being created.
- At 25 Hz and multi-Hz, abrasive wear that occurs due to metal particles created by shear strain was observed.

(3) From the seat insert wear mechanism, the following phenomena were observed:

- At 10 Hz, adhesive wear occurring at the beginning stage of metal wear was primarily observed.
- At 25 Hz and multi-Hz, surface fatigue wear was noticed because the seat insert was made from a sintered iron powder.

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