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Design and operation of a high temperature wear test apparatus for automotive valve materials

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ABSTRACT

A current trend in the automotive industry is to reduce the engine size while increasing power. The valve and valve seat perform the functions of ensuring the entry of air and combustible material, the output of combustion gases and sealing during the compression and combustion processes. As a result, the pair valve and seat are the most critical components in high-efficiency engines. To ensure the robustness of their operation while providing clean combustion and low emissions, the use of the correct materials is required. The high temperatures of the exhaust gases, the velocities of the valves and the high operating pressures are several of the parameters that cause wear on the valve seats and valves. The materials used to create the valve must be characterized by good workability, high wear resistance, good mechanical strength and good fatigue and corrosion resistance at high temperatures. However, the tests applied to develop new materials are limited to lower temperatures than those expected in the next generation of combustion engines. In this study, the development of a new valve seat and valve test machine for high temperatures is presented. A comparison of the currently available designs of apparatuses for this purpose is also presented with the new proposed design. The results of testing the valve seats and valves using this new design are presented and evaluated along with the results of the standard test machines.

1. Introduction

Currently, vehicle combustion engines are designed to be smaller but with greater output power, producing lighter powertrains and higher overall automobile efficiency. Smaller engines also save space under the hood, where other devices such as electrical motors and accessories are housed, allowing cars to utilize hybrid technology and potentially other energy sources. One of the challenges posed by the worldwide automotive industry is for 1.2-liter cylinder engines to achieve power approaching 200 hp [1]. Today, 1.4-liter engines deliver a power output near 100 hp. One of the strategies for obtaining greater power is to employ a turbo-compressor that increases the mixture volume in the combustion chamber at a higher pressure, improving the combustion power. Other alternatives include improving the fuel combustion, the use of lighter and more resistant materials, decreasing friction and improving heat exchange, etc. These changes typically lead to higher temperatures and pressures in the combustion chamber and thus require exhaust valves and valve seats that will operate at higher temperatures; these new operating conditions are not currently supported by available materials [1].

Many changes in the valve and valve seat materials, processes and designs have contributed significantly to increased engine durability and efficiency; however, there is still a significant amount of research to be done [2]. The engine valve and the seat insert that are used in engines must operate normally in severe environments at high temperatures and pressures and must perform as designed for a long period of time [3]. The development of new materials for automotive engine valves is based on the need for increased service durability, low material cost and good manufacturing characteristics, both for the valves and the valve seats [4]. The following characteristics must be considered: high-temperature resistance, wear resistance, corrosion resistance, toughness, high-temperature fatigue resistance and high thermal conductivity [5]. Different researchers have developed test apparatuses for wear analysis of these two components. The equipments developed by Lewis [6], Wang et al. [7], Chun [8], Slatter et al. [9], and Ramalho et al. [10] were used as references for the new design proposed.

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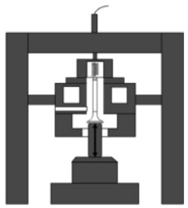
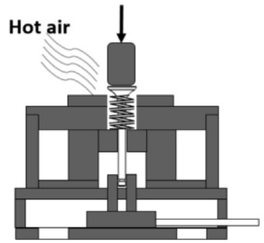
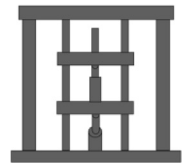
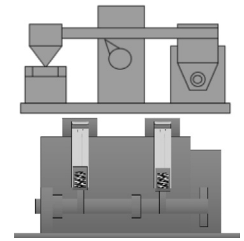
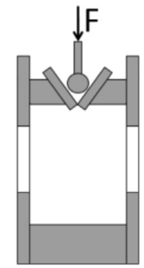
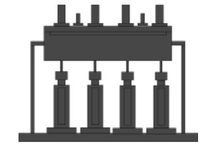
Table 1
Primary characteristics of the currently available valve and seat test machines.

Benchmarking analysis						
	Wang (1996)	**Lewis (2002)**	**Chun (2007)**	**Slatter (2009)**	**Ramalho (2009)**	**Mascarenhas (2014)**
Concept						
Construction features	Structure based on a universal testing machine	Valve mounted upside down. The spring opens the valve	Structure based on a universal testing machine	Two separated experiments. Reciprocating movement from a cam. Twin valve test rig	Does not test the component, test material	Four independent combustion chambers and four actuators
Operating characteristic	Temp: 180, 570 °C Load: 2 kN to 22 kN Spin: 4 rpm Off Set 0.76 mm	Temp: 130 °C Load: 6 kN to 18.6 kN Freq: 10 Hz Spin: 1 rpm Off set: 0.25 mm	Temp: 760 °C Load: up to 39 kN Freq.: 50 Hz Spin: 4 rpm	The operating speed of a 2.2 KW motor is maintained and controlled by a speed controller.	Temp: 20, 200 and 400 °C Freq.: 10 Hz	Temp: 900 °C Load: 1 kN to 25 kN Spin: 4 rpm Off Set: 0.1 to 10 mm Freq.: 50 Hz
Time/number of cycles	1.5×10^3 Up to 3.4×10^6	2.4×10^4 Up to 5.5×10^4	2×10^6	100 h to 3.6×10^6	Not mentioned	Flexible
Analysis method	Scanning profilometry, SEM, EDS	Optical microscopy	Optical laser scanning, SEM, EDS, scanning profilometry	Optical microscopy, profilometry	SEM, EDS, scanning profilometry	Chemical Analysis, Stereoscopy, Metallography, MEV, EDS, Surface, Macro- and Micro-Hardness
Analysis quantitative	Wear depth	Wear depth	Rmax	Wear volume	Wear volume	Rt and Rmax

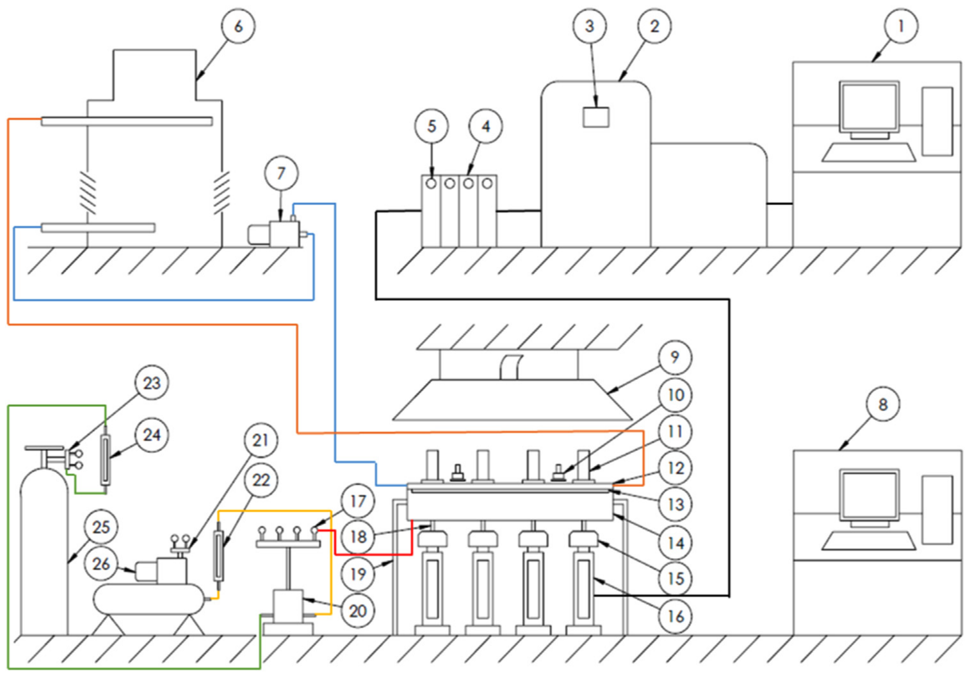


Fig. 1. Design layout of the wear test apparatus.

The proposed design was developed to simulate the new operating conditions to which the valves and valve seats will be subjected in Otto and diesel internal combustion engines. The apparatus evaluates the performance of new materials and can identify the least costly materials that can best meet the product requirements, considering the life cycle analysis of each material [11].

This study has three primary objectives. The first is to present the development process of the test apparatus for valves and valve seats at high temperatures. The second objective is to benchmark the new design with equipment similar to that used to evaluate these engine components. The third objective is to propose an experimental method to be used to test and evaluate new materials for use as internal combustion valves and valve seats.

2. Design and development of the wear test apparatus

A comparison of the current design to those for other valve wear test methods is presented in this section.

The wear test apparatus developed by Wang [7] does not contain a valve rotation device; its construction is based on the adaptation of a hydraulic universal testing machine that is servo-controlled with two columns, in which one valve is tested at a time.The test apparatus developed by Lewis [6] tests the influence of the valve impact speed in an isolated manner and at low temperatures, however the wear behavior at room temperature does not provide insight into the material's behavior at high temperatures. Although Chun [12] has tested aspects such as changes in speed, temperature, load and friction between the valve and valve seat under the operating conditions of an internal combustion engine, a load of 4 kN was used, which is below the equivalent combustion force; his wear test apparatus also tests only one valve at a time. To investigate the wear mechanism based on the cycle numbers (i.e., mileage) and Hz (rpm), Chun used Rmax (maximum roughness measured between the major peaks and valleys of one segment) instead of the wear depth for the following reasons: in the seating faces of the valve and valve seat inserted after the completion of a test, there is a section above the section with no wear; in some cases, the valve seat insert does not have a section with no wear that can be used as a reference point because wear occurs on the entire seating face [3]. The same approach was used in this study.The wear test apparatus developed by Slatter et al. [9] to investigate the wear in valve materials was divided into two different devices. The first device was responsible for testing a sample of the valve material and consisted of an arm with a hardened tip to measure how many times the valve moves away from the sample by a command shaft of a diesel engine and thus impacts the sample using a spring. The second device was intended to test the combined effects of the material to be tested with the geometric shape of the valves. Because this test uses the final geometry of the valve and seat, the interface effects and the wear reaction due to changes in the contact angles can be analyzed; this allows the specific wear test apparatus to test two components while allowing the comparison of two materials in the same test. In this study, four sets were designed for testing based on Slatter's [9] positive results that enabled testing of two valves and valve seats. The work developed by Ramalho et al. [10] was focused on the effects of temperatures up to 400 °C on sliding surfaces between the valves and valve seats. However, the test was not based on the real geometry of the valves and valve seats; instead, cylindrical specimens were used. This could lead to inconclusive results because the geometry also affects the dynamic and tribology behaviors of the wear phenomena. Table 1 shows a summary of each current design and its primary characteristics.

The wear test apparatus used in this study based on the concepts developed by Wang [7], Lewis [6], Chun [2], Slatter [9] and Ramalho [10] and attempts to produce more complete results and can test several valves simultaneously. The following sections show the development method applied.

2.1. Description of the wear test apparatus used for testing valves and valve seats

From the functional structure of the product, the solution principles for each function were generated based on a morphological matrix. The design layout is given in Fig. 1. Table 2 presents a list and a summarized description of the different systems, subsystems and components.

Fig. 2 presents the general configuration of the test apparatus developed for the accelerated wear tests of the valve and valve seat. The apparatus consisted of 8 systems: 1 – valve spring; 2 – valve pre-load; 3 – cooling system; 4 – valve seat off set; 5 – heating system/combustion chamber; 6 – loading system; 7 – exhausting system and 8 – data acquisition system. The materials used were carbon steel for the steel structure of the block and the combustion chambers; Nimonic 80A (high temperature precipitation hardening nickel base alloy) for the stems of the load applicator; and AISI 310 stainless steel for the others components. One of the most important components is the combustion block, which contains the corrosive combustion environment and resists the high-temperature operation. There are 4 combustion chambers with the capacity to simultaneously test one valve-valve-seat pair per chamber. To perform a complete cycle, an opening movement is produced from a pressure that is applied to the top of the valves by springs; then, a pressure is applied to the bottom of the bench-scale to the valves head by hydraulic actuators to perform the closing movement. Forces are applied that simulate the closing condition and the pressure imposed by the combustion chamber. In the bubble shown in Fig. 3, the detail of the spring force applicator to the valve shaft is shown. A force equivalent to the compression and explosion forces are applied to the bottom, and a rod transmitted the force from the actuator to the valve. The support plate of the valve seats is mobile and adjusted before the tests to promote misalignment between the valves and the valve seats [11]. Fig. 3 shows a picture of the primary components of the equipment and how the misalignment for the accelerated wear testing of the valve and valve seats is obtained.

Table 2
Description of the wear test apparatus systems and subsystems.

01 Hydraulic control system	02 Hydraulic pump
03 Hydraulic control panel	04 Accumulator system oil pressure
05 Pressure indicator for cylinder	06 Cooling tower
07 Pump cooling system	08 Data acquisition temperature
09 Hood exhaust system	10 Electric gear motor (spin valve)
11 Valve spring bracket preload	12 Cooled top plate
13 Intermediate plate supporting the valve seats	14 Structural body, with combustion chambers
15 Load cells for actuators	16 Hydraulic actuators
17 Mixer of LPG distributor	18 Hydraulic actuator rods
19 Holder test bench	20 Mixer of gases, LPG and air
21 Pressure regulator for compressed air system	22 Flow regulator for compressed air
23 Pressure regulator for LPG	24 Flow regulator for LPG
25 LPG cylinder	26 Air compressor

Wear acceleration is imposed by the misalignment of the valve seats in relation to their corresponding valves; the intensity and frequency of the load applied during the test; and the operating temperature to which these components are exposed [11].

3. Analysis of the proposed method

This study requires that the experiments must be performed at conditions that simulate the real use of the valves and valve seats as accurately as possible. The method used for the evaluation process includes the design of the experiments, the selection of a material for testing, the assembly of the components to be tested in the apparatus, the definition of the parameters and the test itself, the removal of the valves and the valve seats, the cleaning of the components, and the characterization of the tested material and associated analyses [11].

The first step must be the design of the experiment to combine the different materials and factors. The selection of the valves and valve seats must be made in pairs because their performance is linked. Properties like hardness and toughness must be similar between the two components so that the pair has a long lifespan. The assembly of each component must be made following the test apparatus procedure. The experiment design must be randomized to avoid noise and systematic errors. After performing the experiments, the valve and valve seat' materials are evaluated. Based on each material characteristics and the degree of corrosion and adherence, the cleaning procedure of the valve and valve seat must be defined.

In Fig. 4, the profile capture of the worn/contact surfaces is presented. After measuring the surface roughness, the valves and valve seats were transversely cut to evaluate the microstructure of the material. The purpose of this procedure is to evaluate if the high temperature cycles influenced the entire material; additionally, this procedure allows the microhardness of the material to be measured both on the surface and in the core of the valve and seat. The analysis of the results of the evaluated materials will define what materials should be selected for additional testing in the bench-scale or further testing in assembled engines on dynamometers. The materials that progress through these phases should have lower wear on the surfaces, no superficial cracks or pits and few microstructure changes. Because the test apparatus has four

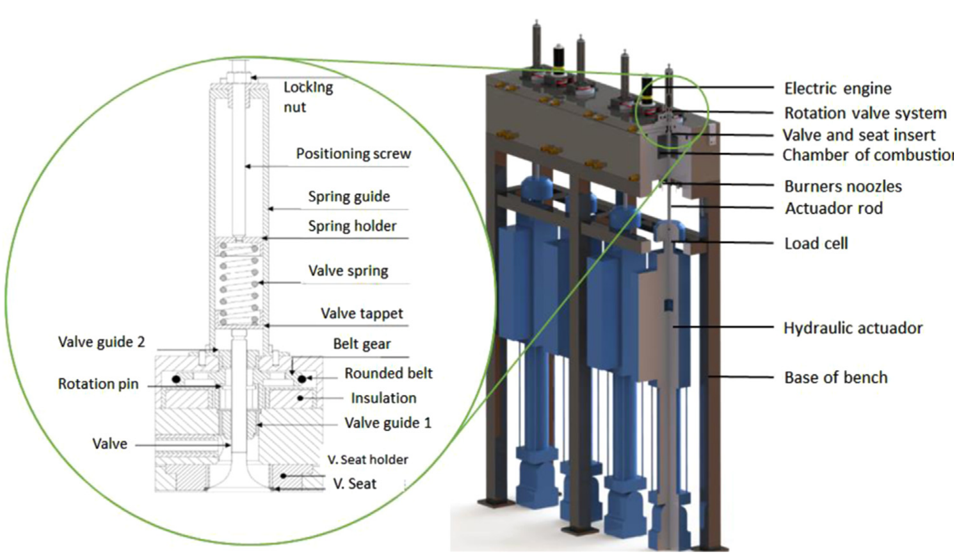


Fig. 2. General setup of the wear test apparatus used for testing the wear on the valves and, detailed in the bubble, the valve seats and the valve loading system.

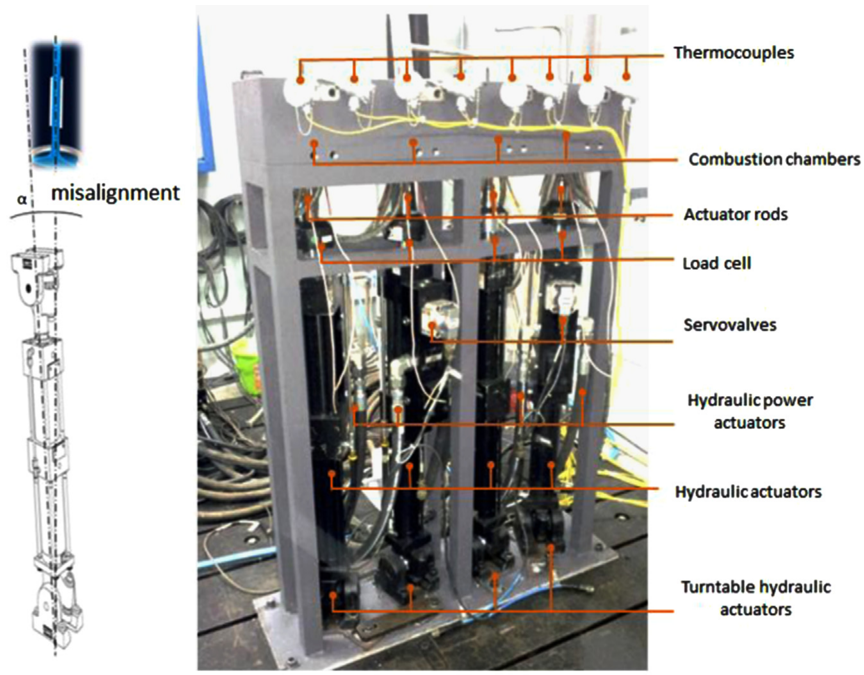


Fig. 3. Wear test apparatus.

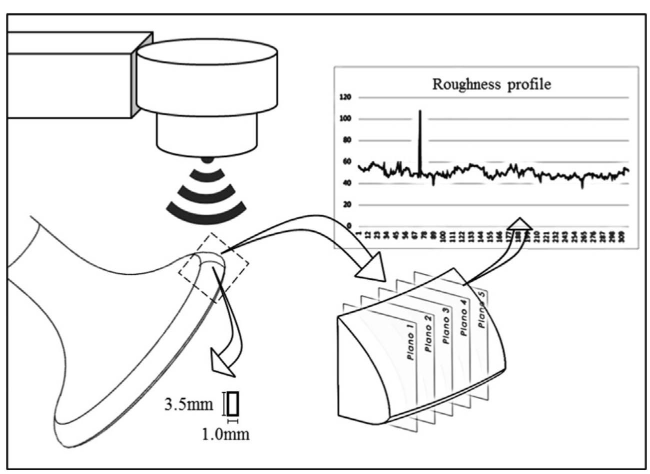


Fig. 4. 3D and 2D roughness profile capturing sequence.

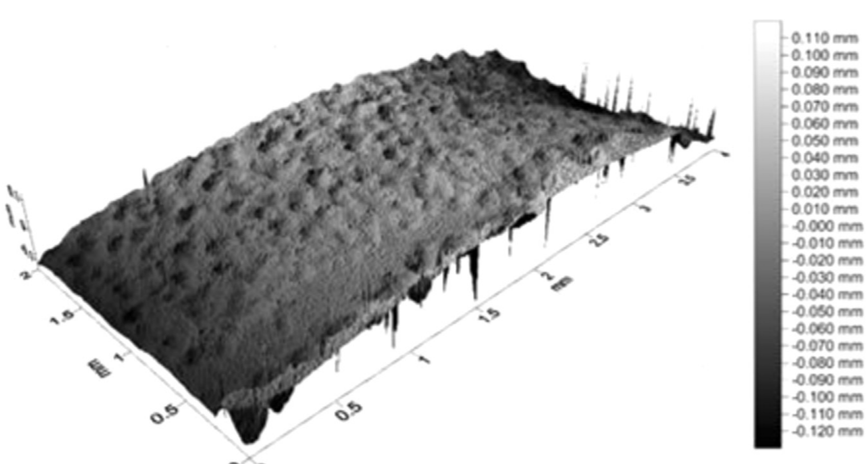


Fig. 5. 3D roughness profile obtained by optical profilometer from the contact surface of the valve subjected to 750 °C and a load of 6 kN.

chambers, the researcher must use them as blocks on the design of experiment; this is necessary because small differences including temperature variations and small assembly differences may be present. Testing the samples in groups can help mitigate these effects on the results.

3.1. Measurement of the roughness profile

A quantitative wear evaluation was performed using the rugosity and depression measurements at the contact faces of the tested valves and valve seats. Fig. 5 indicates the sequence of the activities developed for capturing the roughness and depression profile at the valves and valve seats' contact faces. Step 1 includes the positioning of the valves at an inclined base angle of 45°; step 2 includes the selection of an area to be measured; step 3 includes the collection of 3D surface imaging; step 4 includes the division of the 3D imaging into 5 specimen plains; and step 5 includes the generation of 2D rugosity graphs. In this process, the maximum rugosity (i.e., Ry or Rmax) and the total rugosity (Rt) were calculated for the faces of each component. These measurements were performed based on DIN EN ISO 4287.

4. Performance evaluation

Experiments were performed to evaluate the reliability and significance of the results of the proposed method and equipment. Three series of experiments were performed testing eight valves and valve seat pairs. In total, 24 valves and an equal number of valve seats were tested; each run tested four valves and four valve seats. The statistical software Mintab version 6 was used to support the design and evaluate the results of all experiments.

The material characterization was performed using optical emission spectroscopy. Then, the components were evaluated using a stereoscope and a scanning electron microscope (SEM) where the worn surface can be observed. An SEM with Energy Dispersive Spectroscopy (EDS) also provided information about the chemical analysis of the surface. Thus, EDS tests were performed with the following parameters: a fit filter; Chi-squared value = 1.340; error = ± 1 sigma; correction method = Proza (Phi-Rho-Z); acc. voltage = 30.0 kV; and takeoff angle = 35.0°. This method could help to confirm wear, adherence, material loss and oxidation phenomena.

In this work, the materials used were SAE 4340 steel for the valve seat and SAE EV12 21-2N austenitic steel for the valve. At the valve's seat region, the valve is locally coated with *Stellite* to increase wear resistance. Chemical composition of valve is shown in Table 3.

4.1. Experiment 1 – design

Experiment 1 was designed to test if the temperature applied at the two temperature levels would produce a difference in the results when using the bench-scale testing apparatus; this was done to evaluate if the apparatus had an effective use at the temperatures that were experienced by the valves and valve seats. The lower temperature used was set to 550 °C, and upper was set to 750 °C. A current V6 engine reaches about 760 °C in some portions of the valve. Advanced engines must be tested in the range of 850–900 °C; however, the materials selected for these tests do not support these conditions. The valves and valve seats were standard parts acquired from the market as replacement automotive parts and are designed for an engine's exhaust system. The factors of frequency (8 Hz), load (6 kN), misalignment (0.3 mm) and valve spin rotation (On) were held constant for 30 h during experimentation (864,000 cycles). The second factor tested was the four chambers of the testing apparatus. The idea was to identify if the chambers influenced the results. Four different outputs were measured: the maximum height roughness on the valve contact surface (V. Rmax); the total height roughness on the valve contact surface (V. Rt); and the corresponding measurements on the seat surface (S. Rmax and S. Rt). Forsberg et al. [13], Slatter [9] and Chun [2] also used these roughness profiles to evaluate their results.

Table 3
Chemical composition of the materials used for the valve in this work: before and after the test.

Wt	Fe	Ni	Cr	Mn	C	Mo	Si
After the test	68.1	1.75	21.0	8.38	0.379	0.0545	0.0979
Before the test	69.0	1.76	20.5	7.87	0.353	0.808	0.103

Table 4
ANOVA results for experiment 1.

Source	DF	Seq SS	Adj SS	Adj MS	*F*	*P*
Analysis of variance for V. Rmax using adjusted SS						
Temperature	1	804.6	804.6	804.6	7.24	0.074
Chambers	3	681.3	681.3	227.1	2.04	0.286
Error	3	333.5	333.5	111.2		
Total	7	1819.3				
S = 10.5429 R-Sq = 81.67% R-Sq(adj) = 57.23%						
Analysis of variance for S. Rmax using adjusted SS						
Temperature	1	764.8	764.8	764.8	36.86	0.009
Chambers	3	397.13	397.13	132.38	6.38	0.081
Error	3	62.24	62.24	20.75		
Total	7	1224.16				
S = 4.55479 R-Sq = 94.92% R-Sq(adj) = 88.14%						
Analysis of variance for V. Rt using adjusted SS						
Temperature	1	1046.99	1046.99	1046.99	15.35	0.03
Chambers	3	711.3	711.3	237.1	3.48	0.167
Error	3	204.68	204.68	68.23		
Total	7	1962.97				
S = 8.25997 R-Sq = 89.57% R-Sq(adj) = 75.67%						
Analysis of variance for S. Rt using Adjusted SS						
Temperature	1	798	798	798	40.02	0.008
Chambers	3	308.08	308.08	102.69	5.15	0.106
Error	3	59.82	59.82	19.94		
Total	7	1165.9				
S = 4.46537 R-Sq = 94.87% R-Sq(adj) = 88.03%						

4.2. Experiment 1 – results and analysis

The results of the analysis of the data from experiment 1 indicated that the four chambers did not influence the roughness results. In Table 4, the analysis of variance is presented for each of the four roughness valves measured. The results show that for the valve's Rmax, it was not possible to affirm at a 95% confidence interval that the temperature had influenced the surface rugosity; however, the *P* value was only slightly below the level of significance. It is possible that noise during the experiments, surface cleaning and surface roughness measurement influenced the results. In the other results based on the measurements of the valve's Rt and the seat's Rmax and Rt, it was possible to affirm that the temperature did influence the results (the *P* value was below 0.05).

The roughness measurements were obtained using an optical profilometer that could return a 3D profile of the measured surface. Fig. 5 shows one of the measurements as an example. The roughness profiles were taken by reading five parallel planes of the 3D surface.

In Fig. 6, the valve surface image obtained by the SEM is shown. There are indications that the material was pulled out (see the arrows in Fig. 7), pulled out, suggesting the possibility of adhesive wear; this behavior was also identified by Wang [7].

4.3. Experiment 2 – design

The second experiment was designed to evaluate the influence of the temperature and the load on the wear of the valves and valve seats. A design of a two level factorial (i.e., 2^2) was used with two replicas. Table 5 presents the treatments and the levels of each tested factor. It is necessary to understand that the load varied from zero to the level indicated for each treatment on the table. These two levels of loads were above those experienced in real conditions. The idea was to produce severe conditions to accelerate the test and the outputs levels so that changes could be more easily detected. Wang et al. [7] used loads from 2 kN to 39 kN; this level was not considered because it is significantly different from those found in an engine and could lead to misinterpretation. The fixed effects for this experiment included the frequency (8 Hz), the

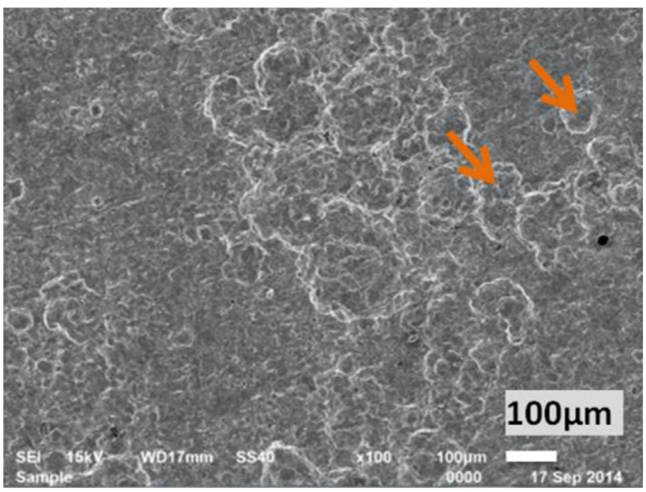


Fig. 6. SEM micrography of a valve surface tested at 750 °C under a load of 6 kN after 844,000 cycles.

Table 5
Experimental planning for experiment 2.

Treatment	Factor	
	Load (kN)	Temperature (°C)
I	6 (−)	550 (−)
A	9 (+)	550 (−)
B	6 (−)	750 (+)
AB	9 (+)	750 (+)

Table 6
ANOVA results for experiment 2.

Source	DF	Seq SS	Adj SS	Adj MS	*F*	*P*
Analysis of variance for V. Rmax (coded units)						
Load	1	3.001	3.001	3.001	0.20	0.680
Temperature	1	193.061	193.061	193.061	12.67	0.024
Load*Temperature	1	8.405	8.405	8.405	0.55	0.499
Error	4	60.942	60.942	15.235		
Total	7	265.409				
S=3.90326 R-Sq=77.04% R-Sq(adj)=59.82%						
Analysis of variance for V. Rt (coded units)						
Load	1	0.026	0.026	0.026	0.00	0.967
Temperature	1	251.328	251.328	251.328	18.11	0.013
Load*Temperature	1	3.001	3.001	3.001	0.22	0.666
Error	4	55.518	55.518	13.879		
Total	7	309.874				
S=3.72552 R-Sq=82.08% R-Sq(adj)=68.65%						
Analysis of variance for S. Rmax (coded units)						
Load	1	0.525	0.525	0.525	0.01	0.939
Temperature	1	96.675	96.675	96.675	1.23	0.330
Load*Temperature	1	67.687	67.687	67.687	0.86	0.406
Error	4	314.989	314.989	78.747		
Total	7	479.875				
S=8.87396 R-Sq=34.36% R-Sq(adj)=0.00%						
Analysis of variance for S. Rt (coded units)						
Load	1	3.445	3.445	3.445	0.05	0.834
Temperature	1	133.416	133.416	133.416	1.93	0.237
Load*Temperature	1	46.803	46.803	46.803	0.68	0.457
Error	4	276.568	276.568	69.142		
Total	7	460.233				
S=8.31517 R-Sq=39.91% R-Sq(adj)=0.00%						

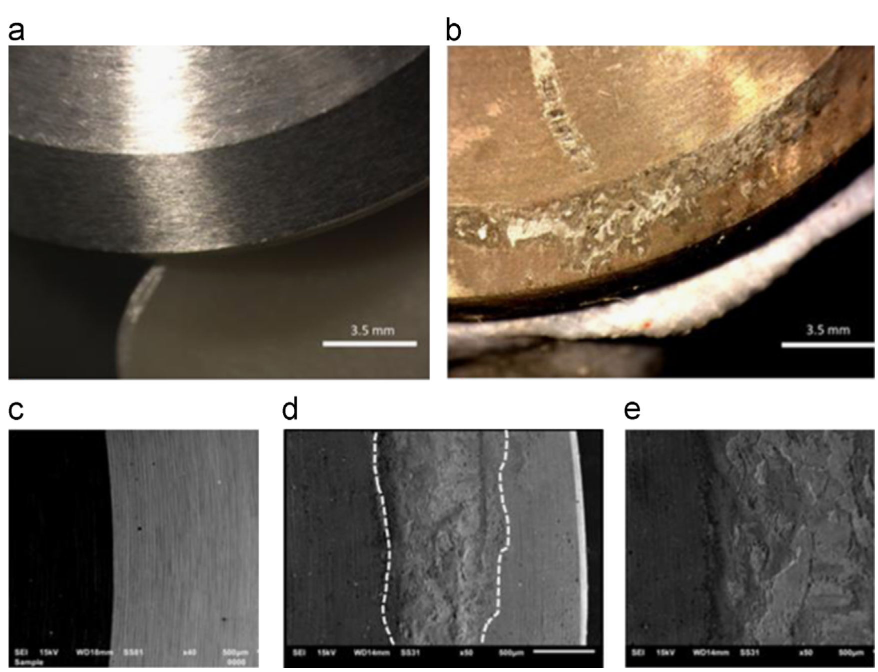


Fig. 7. Microscopy analysis on valve's surface before and after the tests showing additional material attached to the surface of the valve.

misalignment (0.3 mm) and the rotation/spin of the valves (On). The experiment ran for 10 h at the set frequency, generating 288,000 cycles. This frequency is equivalent to the same condition of a motor running at 960 rpm. The misalignment used should induce a premature failure of the valves. This value is near 0.25 mm, which was used by Lewis [6]; conversely, Wang [7] used a larger misalignment of 0.76 mm.

4.4. Experiment 2 – results and analysis

The results were measured following the same procedure as used in the first experiment. An analysis of variance was performed and is presented for each output in Table 6. It was found that the valve was the only component that showed wear (Rmax and Rt) on the contact surface that could be correlated to one factor: temperature. The load factor did not show statistical significance at the 95% confidence level to affect the wear on the valves or valve seats' surfaces; this might have occurred due to the relatively low number of cycles applied in this experiment. However, the wear level found agreed with the numbers reported by Wang [7]. No interactions between the temperature and the load were identified. It is probable that other sources of noise were present during the tests because significant differences were found between the model and the data using the ANOVA test, particularly in the seat roughness. Compared to what was found in experiment 1, the temperature shows a negative influence on the surface roughness, decreasing the Rmax and Rt at higher levels.

SEM analyses on valve surface after tests shows no evidence of cracks or corrosion pits. Quantitative Energy Dispersive Spectroscopy (EDS) analyses was performed on different regions of the valve's surface and it appears that due to repeated and intermittent loads and high temperature, valve seat material was detached and adhered on the valve's surface. This assumption was confirmed analyzing the valve before and after by microscopy means where some additional material was observed attached to the surface of the valve (Fig. 7a and b). In some regions the Stellite coating was preserved (Fig. 7d and e).

4.5. Experiment 3 – design

The objective of experiment 3 was to test the influence of the valve's rotation/spin, the frequency of opening and closing and the load applied on the wear the components. The design of this experiment is presented in Table 7. The experiment was performed at 25 °C and with a misalignment of 0.3 mm. The total number of cycles was set to 288,000; one set ran for 13.3 h, and the other for 8.89 h because they were dependent on the frequency used. Two replicas were used in this experiment.

Table 7
Experimental planning for experiment 3.

Treatment	Factor		
	Load (kN)	Frequency (Hz)	Spin
I	6 (−1)	6 (−1)	Off (−1)
A	9 (+1)	6 (−1)	Off (−1)
B	6 (−1)	9 (+1)	Off (−1)
C	6 (−1)	6 (−1)	On (+1)
AB	9 (+1)	9 (+1)	Off (−1)
AC	9 (+1)	6 (−1)	On (+1)
BC	6 (−1)	9 (+1)	On (+1)
ABC	9 (+1)	9 (+1)	On (+1)

Table 8
ANOVA results for experiment 3.

Source	DF	Seq SS	Adj SS	Adj MS	*F*	*P*
Analysis of variance for V. Rmax (coded units)						
Load	1	31.047	31.047	31.047	6.16	0.068
Spin	1	528.125	528.125	528.125	104.76	0.001
Load*Spin	1	391.720	391.720	391.720	77.70	0.001
Error	4	20.170	20.170	5.041		
Total	7	971.060				
S=2.24532 R-Sq=97.92% R-Sq(adj)=96.37%						
Analysis of variance for V. Rt (coded units)						
Load	1	74.970	74.970	74.970	7.08	0.056
Spin	1	619.340	619.340	619.340	58.51	0.002
Load*Spin	1	500.070	500.070	500.070	47.24	0.002
Error	4	42.344	42.344	10.590		
Total	7	1236.730				
S=3.25361 R-Sq=96.58% R-Sq(adj)=94.01%						
Analysis of variance for S. Rmax (coded units)						
Load	1	241.230	241.230	241.231	29.10	0.006
Spin	1	26.100	26.100	26.100	3.15	0.151
Load*Spin	1	361.670	361.670	361.670	43.62	0.003
Error	4	33.160	33.160	8.291		
Total	7	662.160				
S=2.87936 R-Sq=94.99% R-Sq(adj)=91.24%						
Analysis of variance for S. Rt (coded units)						
Load	1	390.180	390.180	390.180	31.81	0.005
Spin	1	60.670	60.670	60.670	4.95	0.090
Load*Spin	1	461.020	461.020	461.020	37.58	0.004
Error	4	49.070	49.070	12.270		
Total	7	960.930				
S=3.50237 R-Sq=94.89% R-Sq(adj)=91.06%						

4.6. Experiment 3 – results and analysis

In the third set of experiments, the results show that the spin and load factors do influence the roughness of the surface. The frequency, however, did not have any effect on the results and was thus excluded from the ANOVA. The spin factor showed influence over the Rmax and Rt. Without the spin, the roughness was found to be higher and vice versa. The load factor showed a statistically significant effect for only the valve seat; a higher load tended to produce a higher Rmax and Rt. In the roughness of both the valve and the valve seat, there was significance in the interaction between the load and spin factors with Rmax and Rt (Table 8).

4.7. Discussion

The tests at low temperatures were inconclusive due to low roughness differences found in the valves and seats for different levels of tests. Temperature did influence the results; however, in experiment 1, where only the temperature was tested as a factor, higher temperatures caused the roughness to increase. Conversely, the results of experiment 2 showed the opposite trend: increasing temperature decreased the roughness. The difference between the first and second experiments might have caused this difference in the roughness results. The duration of the experiments was different: the first experiment ran for 30 h, and the second ran for 10 h at the same frequency. It is possible that in the beginning of the process, the temperature helps to soften the material, decreasing its hardness and strength allowing the occurrence of adhesive wear between the valve and valve seat; later, the material adhesion between seat and valves and constant load–unloading cycles might have increased the roughness of the specimens. Further experimentation is required to prove this non-linear behavior. No interaction was noted between the temperature and the load.

The results in the first experiment helped to evaluate the chamber's influence on the results. It was possible to confirm that the chamber did not significantly influence the results. This is a good result because the possibility to run four tests at the same time is one of the goals of the bench-scale testing apparatus proposed in this work. For future experiments, it is necessary to design experiments using the chambers as a set of blocks; this could help to mitigate problems such as operator assembly errors and different heating/cooling rates provided for each chamber.

Additionally, the apparatus has not been tested to its limits; it was design to work with an upper limit of 1 050 °C and this work has been tested to 750 °C. To date, it has presented good results with regard to the wear of the components in different conditions, and its dimensions allow the testing of valves up to a diameter of 52 mm and a height of 155 mm; this covers a wide range of automotive combustion engines up to light trucks.

5. Conclusions

The bench-scale testing tribometer developed for the simulation of tribological behaviors in the valve-seat pair was demonstrated to be adequate for imposing the thermal conditions and mechanical stresses usually observed in a real engine operation scenario, allowing for the real evaluation of the valve and valve seat materials.

The possibility of testing 4 valve-valve-seat sets at once by either repeating the same conditions for four sets or by applying different test conditions was one characteristic of the experimental equipment developed for accelerated wear testing.

This testig apparatus could be used to reduce the time required to develop new valve and valve seat materials while considering their operation at high temperature; this capability has not been available in any other wear test apparatus developed to date in the literature.

The apparatus can also be used in combination with dynamometers to reduce the time-to-market for new valve materials. Further research on the correlation between the results given by this equipment and the results found when using a dynamometer is already in development and should provide suggestions for test corrections or even the removal of the need for dynamometer tests.

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