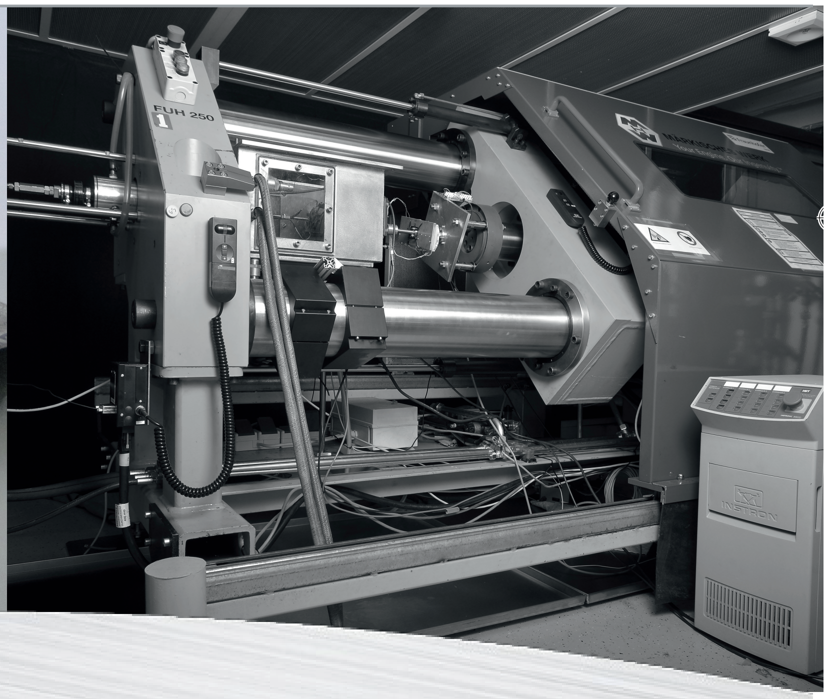
Valve Wear in lean-burn Gas Engines

From engine tests of components to a unique tribological test rig.



MÄRKISCHES WERK

Your Engine. Our Ingenuity.™

INTRODUCTION

The continuous development of large bore gas engines to achieve higher efficiency and lower total cost of ownership means that previously unknown limits of materials, designs or manufacturing processes can reveal themselves. In terms of insignificantly changed components, the operating conditions may have modified, which can exhibit wear. Valve wear is an example that links the global tightening of emission legislations and the striving for more efficiency. That means measures such as lean-burn combustion processes, after-treatment systems, turbocharging or constantly increasing of peak combustion pressures (PCP), prevailing to more than 250 bar in current large bore gas engines, have arisen from the dramatic changes in the combustions residues and mechanical component loads. As a result, no protective anti-wear tribofilm can build-up on the valve seating faces [1].

Reviewing the last decades, the elimination of lead [2,3] and sulphur and restriction of particle matters, which all possess anti-wear properties, have aggravated the valve wear subject. These factors push the common valve materials to their performance limits.

Valve wear according to the state of the art for large bore diesel engines is about 0.5 mm after 24,000 operating hours, in other words a wear rate of about 21 nm/h. In contrast to diesel engines, approximately 30-times greater wear rates of about 600 nm/h were measured on several worn inlet and exhaust valves in lean-burn large bore gas engines by the authors, whereas state of the art materials and proven valve designs were used. Currently, acceptable lifetimes can only be achieved by a reduction of efficiency-relevant engine parameters. “Quick-fix” measures are no longer able to cope with this technical challenge. Consequently, there is a need of sustainable approaches based on an in-depth understanding of the wear mechanisms. The key goal of these research activities is the development of reliable solutions in order to achieve comparable lifetimes of modern large bore gas engines as well as diesel ones.

Since the tribology of the wear pair valve spindle/seat ring presents a complex, technical issue, influenced by contact mechanics, material science, chemistry and physics, most of the solutions are randomly found. A number of studies to parameter dependencies upon the valve wear process have been performed such as: component misalignment [4,6,11], PCP [5,6,8,10,11], temperature [5,6,8,10,11], number of cylces [5,8-11], valve rotation [6,8,11], frequency [8-11], closing velocity [8,9] and atmosphere [8,10]. These studies point out that an increasing of misalignment, temperature and PCP corresponds to higher valve wear. On the other hand, a raise of most of these parameters improves the engine efficiency and hence are required. Further, various publications describe specimen wear testers which separate the influence of impact [9,12,13] and sliding wear [14]. Different wear rates and material rankings have been determined but without correlation of neither valve closure nor PCP. There have been systematical approaches for reduction of valve wear; however, especially with regard to the predictability of valve wear the success is moderate. It is known from present tribological research that wear is not a material porperty [15].

Based on an extensive examination of lowly and severely worn wear pairs of inlet [1] and exhaust valve spindles and seat rings in large bore gas engines, a test rig design was developed to simulate the contact situation and environment by separation of the valve cycle into the both phases valve closure and peak cylinder pressure. This provides a means to objectively understand and to relate the primary wear mechanisms of each phase.

A review on existing component test rigs for valve wear was carried out that describes test benches of the researchers Malatesta [4], Wang [5], Lewis [6], Satish [7], Chun [8], Slatter [9], Forsberg [10] and Mascarenhas [11], which were considered as references for a novel test rig, see Table 2.

Beside the wear analysis of different valves from engine tests, this paper presents the first results to provide an overview of the test rig capability. The findings from these investigations justify the need of a novel valve wear test rig for large bore engines, particularly with regard to lean-burn large bore engines running on natural gas. In terms of the potential valve dimensions, this newly designed setup is the world`s largest valve wear tribometer.

ANALYSIS OF VALVE SPINDLES FROM ENGINE TESTS

The following results show the analysis of worn valve spindles hardfaced with two common alloys with regard to valve recession and oxygen penetration. To quantify the valve recession, the wear scar width was measured using 3D-laser scan profilometry. In order to determine the high-resolution oxygen penetration, X-ray photoelectron spectroscopy (XPS) was employed. Hereby, the necessity of a novel designed test rig should be demonstrated.

Examined inlet and exhaust valves are bi-metal friction welded valve spindles (valve disc diameter of about 110 mm, total length about 550 mm) consisting of a martensitic and an austenitic stainless valve steel. The valves were taken from the same type of large bore gas engine. The first set is hardfaced with a Stellite® 12 alloy and was removed from the engine after 250 hours of operation, while the second set is overlaid with a Tribaloy® T400 and was investigated after 5,000 hours of operation.

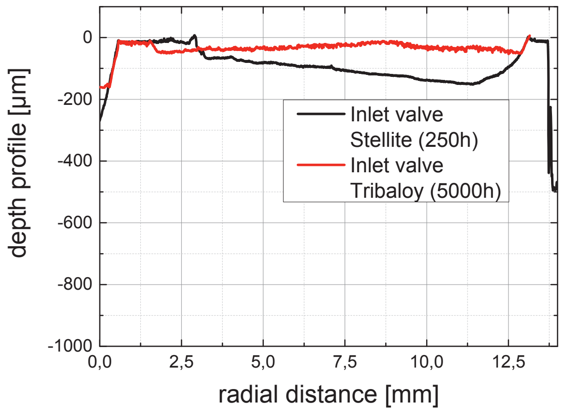


Fig. 1: Wear profiles of inlet valves made of Stellite® 12 (black line) and Tribaloy® T400 (red line) after 250 and 5000 hours of operation, respectively.

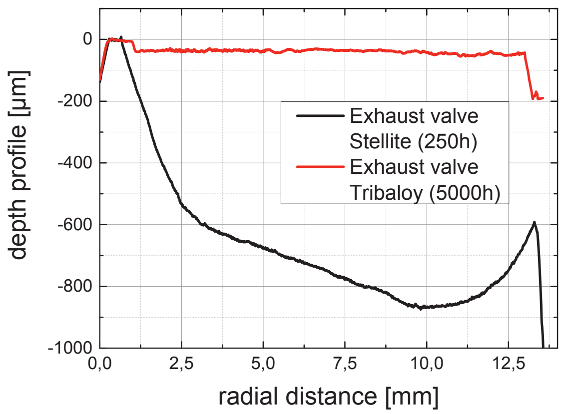


Fig. 2: Wear profiles of exhaust valves made of Stellite® 12 (black line) and Tribaloy® T400 (red line) after 250 and 5000 hours of operation, respectively.

Table 1 shows the composition of both hardfacing alloys.

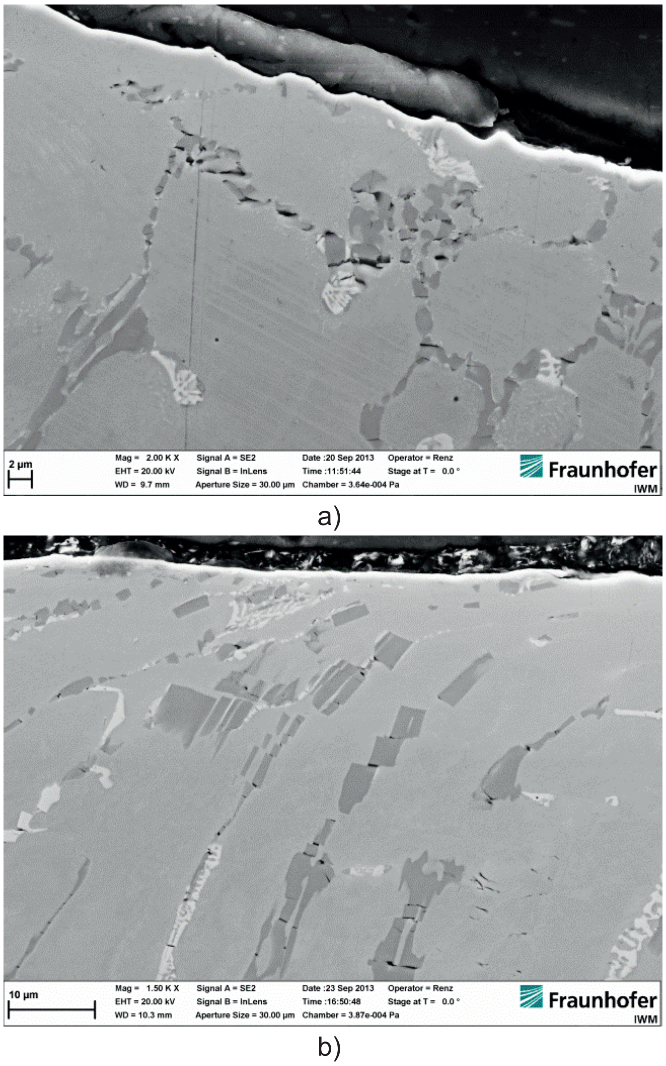


Fig. 3: Subsurface microstructure below the worn seating faces of the Stellite® 12 valves after 250 hours of operation; a) inlet valve, b) exhaust valve.

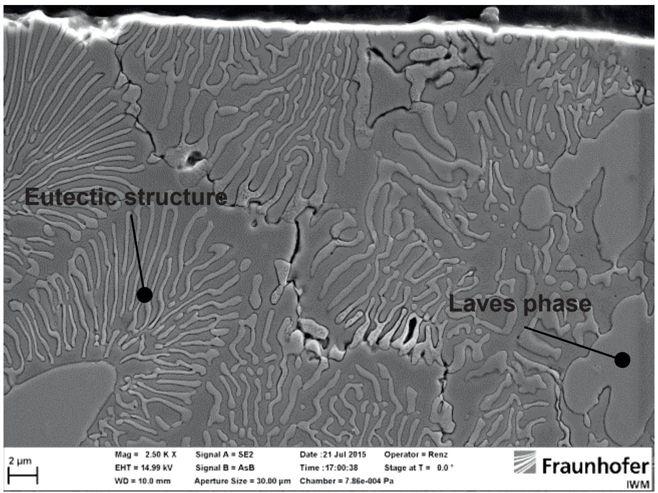
The most prominent difference of the valves is the wear as shown as depth profiles in Fig. 1 and Fig. 2. While the Stellite® 12 valves suffer from high wear (about 150 µm for inlet and 860 µm for exhaust) after 250 hours, the Tribaloy® valves show wear in the range of 20-30 µm after 5000 hours of operation.

Table 1: Nominal chemical composition of the hardfacings in wt-%

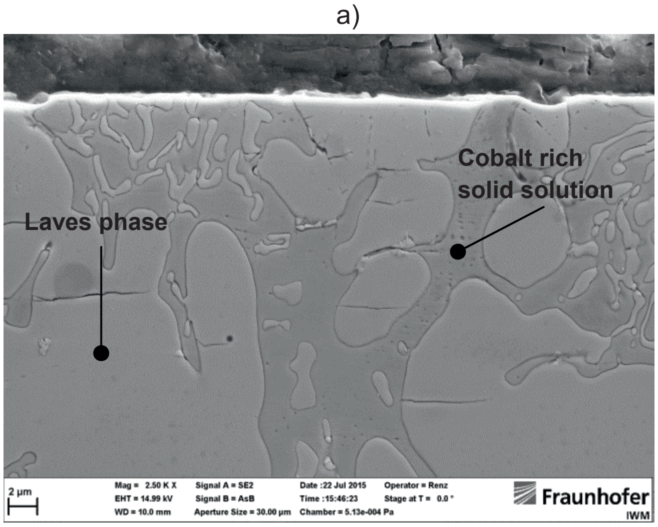
Element	C	Co	Cr	Fe	Ni	Mo	Si	W
Stellite® 12	1.6 – 1.8	Bal.	28,0 - 32.0	≤ 2.0	≤ 3.0	≤ 0.25	1.2 – 1.7	8.0 – 10.0
Tribaloy® T400	≤ 0.1	Bal.	7.5 – 8.5	≤ 2.0	≤ 1.5	27.0 – 30.0	2.2 – 2.9	–

The operation conditions that have been prevailed during the 250 hours and 5000 hours of operation respectively allow a comparative examination. No protective anti-wear tribofilm was formed on the sealing interfaces, see Fig. 3. This stands in contrast with former findings from Forsberg et al. [10], who claimed that the absence of such a film would be necessary to provide stable operation with low wear.

Comparison of the microstructures below the worn valve seating faces gives hints to the reasons for different wear rates. The SEM images in Fig. 3 show cross sections of the Stellite® 12 hardfaced valves. The cobalt rich solid solution contains the dendritically solidified hard carbide network. These carbides are highly fragmented and in the case of the exhaust valve even a shear zone is visible.



a)



b)

Fig. 4: Subsurface microstructure below the worn seating faces of the Tribaloy® T400 valves after 5000 hours of operation; a) inlet valve, cracks are deflected by the lamellar network, eutectic structure with Laves phase b) exhaust valve, cracks constrains to the large Laves phase that is embedded in a cobalt rich solid solution.

The material is shifted from the left to the right side which corresponds with radial material transport by plastic deformation.

Fig. 4 illustrates micrographs of the Tribaloy® T400 hardfaced valves. It becomes clear that the hardfacing process causes different microstructures; eutectic structure of a finer lamellar network as well as embedded hard intermetallic compounds, so-called Laves phase, in a cobalt rich solid solution.

In both cases cracks are visible resulting from mechanical loading during operation. Yet, no further plastic deformation of the material is visible and the cracks are deflected by the lamellar network, or constrained to the large Laves phase.

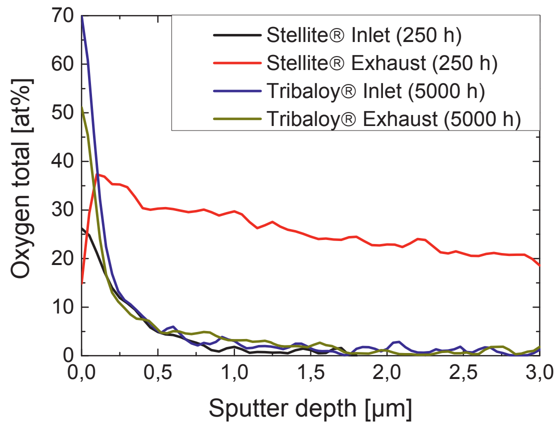


Fig. 5: XPS – comparison of oxygen content

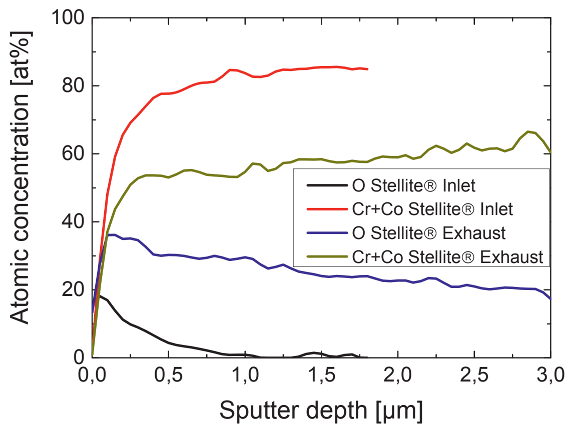


Fig. 6: XPS – correlation of oxygen and chromium-cobalt solid solution in Stellite®12 hardfaced valves.

Both cases indicate an elastic deformation of the matrix during engine operation and fatigue damage of the hard phases. The importance of tribofilm formation has been mentioned before, but the characteristics of such a film are not clearly defined. When the film originates from combustion residues and evaporated oil, it can reach a thickness of several microns and is typical for diesel engines [10,16]. Though, other functional films can be formed in the contact area by surface reactions in contact with the seat ring or just by surrounding gaseous species. These films might have a thickness of several nanometers. Thus, XPS was applied to investigate the valve seating faces in order to characterize the chemical composition of the surface and subsurface area in detail.

The curves in Fig. 5 display the depth profile of oxygen on the worn valve sealing interfaces. The oxygen content between the both Stellite® 12 valves inlet and exhaust is significantly different. Inlet valve shows a drop from 25 at% to < 5 at% over 1 µm, whereas the exhaust valve shows high oxygen content above 35 at% that decreases slightly to 20 at% in 3 µm depth. This indicates a high oxidation of the material which can be accounted to the higher temperature compared to the inlet valve. The curves in Fig. 6 show a correlation of the primary alloying elements cobalt and chromium of Stellite® 12 alloy and the oxygen content which supports the idea of higher oxygen diffusion in the exhaust valve. Yet, it has to be taken into account that the exhaust valve shows much higher wear. The oxygen curves of the valves made of Tribaloy® T400 alloy shown in Fig. 5 are almost identical and show a steep decrease from 50-70 at% to 5 at% within 0.5 µm. In contrast to the Stellite® 12 hardfaced valves, this indicates a high oxidation close to the surface but low diffusion into the bulk material.

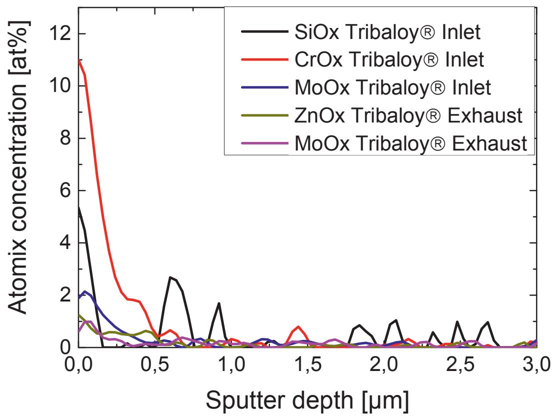
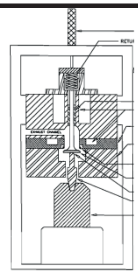
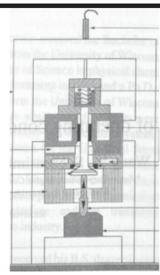
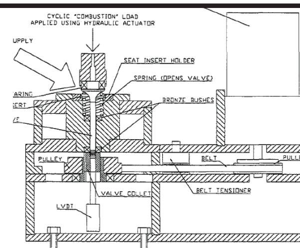
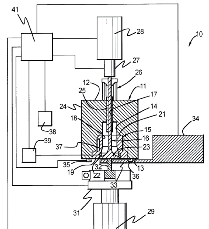
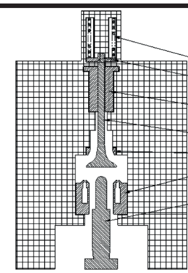


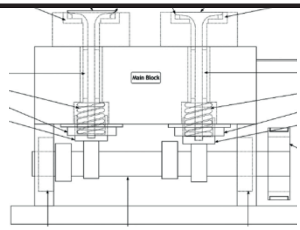
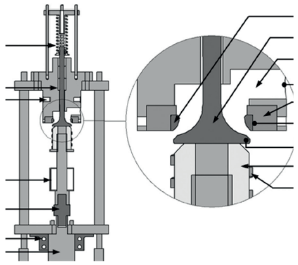
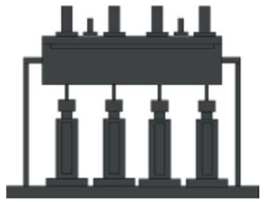
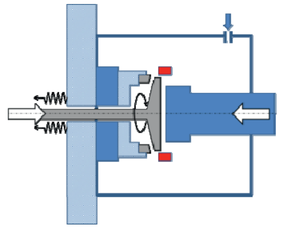
Fig. 7: Oxides measured on the Tribaloy® T400 inlet and exhaust valve wear scars

A closer investigation of the identified metal oxides within the Tribaloy® T400 valve wear scars reveals an oxide layer on the inlet valve which consists of chromium oxide, silicon oxide and small amounts of molybdenum oxide, see Fig. 7. The latter was expected as a tribochemical product that acts as a solid lubricant [17,18]. In the wear scar of the exhaust valve, small amounts of zinc oxide are found together with molybdenum oxide. It can be suggested that the formation of such oxide films minimizes friction and hence lower shear stresses. In effect, this means less valve wear.

Basically these results can be interpreted in several ways. Two different hardfacing alloys lead to different wear responses. Thereby, it is difficult to compare the results directly when not all parameters during operation can be controlled. Finally, it need to be clarified is the wear response material-related, design-related or operation-related. It is precisely for these reasons that a novel test rig should be able to provide application-relevant testing conditions of present large bore gas engines in combination with full control of the discrete parameters.To answer the key question what are the wear-relevant mechanisms of valve wear in present lean-burn large bore engines running on natural gas, the novel test rig is an empowering tool. The development of the test rig is presented in the next section.

Table 2: Overview of component test rigs for valve and seat ring wear simulation published in literature

	Malatesta (1993)	Wang (1996)	Lewis (1998)	Satish (2003)	Chun (2007)
Schematic					
Simulation approach	Combined valve cylce	Combined valve cylce	Combined valve cycle	Combined valve cycle	Combined valve cylce
Load:	3.5 – 38 kN	6 – 24 kN	-	14 – 137 kN	0 – 2 kN
Closing velocity:	0 – 0.25 m/s	-	-	0.6 m/s	0.04 – 0.1 m/s
Valve lift:	0.4 – 12.7 mm	1.2 mm	1 mm	0 - 15 mm	
Temperature:	RT – 816 °C	RT – 650 °C	-	RT – 900 °C	RT – 760 °C
Application	Heavy duty	Heavy duty	Automotive	Heavy duty	Automotive

	Slatter (2009)	Forsberg (2013)	Mascarenhas (2014)	Lehmann (2016)
Schematic				
Simulation approach	Valve closure	Combined valve cylce	Combined valve cylce	Separation of valve cylce into valve closure and peak cylinder pressure
Load:	None	8 – 25 kN	1 – 25 kN	70 – 150 kN
Closing velocity:	Cam	-	-	0.2 – 1.2 m/s
Valve lift:	Cam	3 mm	-	0 – 25 mm
Temperature:	-	RT – 750 °C	RT – 900 °C	RT – 900 °C
Application	Automotive	Heavy duty	Automotive	Large bore engines

DESIGN AND DEVELOPMENT OF THE VALVE WEAR TRIBOMETER

The valve wear test rig was designed as a tribometer to simulate population-relevant large bore engine valves (valve disc diameter of about 90 mm and stem diameter of about 17 mm) and matching valve seat rings, at a component level. In order to grant the controlled variation of all test parameters means the greatest challenge during the design phase. Beside the wear-related behaviour of PCP and valve closing velocity (typical curves shown in Fig. 8), the impact of the temperature as well as atmosphere are difficult to examine in detail.

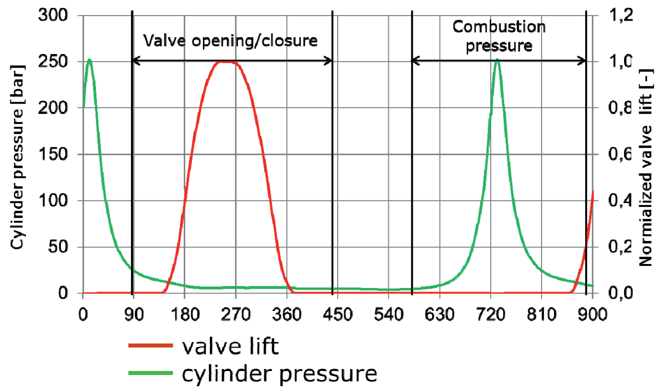


Fig. 8: Cylinder pressure and valve lift vs. crank angle.

The valve wear tribometer was built up on a 250 kN structure-based test frame with two yokes. On the left-sided yoke the test mode I is mounted, on the right-sided yoke the test mode II is assembled. To keep a constant temperature of the components, three cooling circuits are used; two water circuits and one oil circuit.

On each component three thermocouples are applied to monitor the temperature of both valve and seat ring, whereas the signal cables of the valve spindle are passed by a hollow shaft (7). The decoupling of the signal cables is enabled by a slip ring transmitter (8). A force transducer is mounted between the seat ring holder and the test frame, to allow in-situ measurements of the impact forces.

In what follows the environmental chamber and the simulation of both test modes valve closure and PCP are presented.

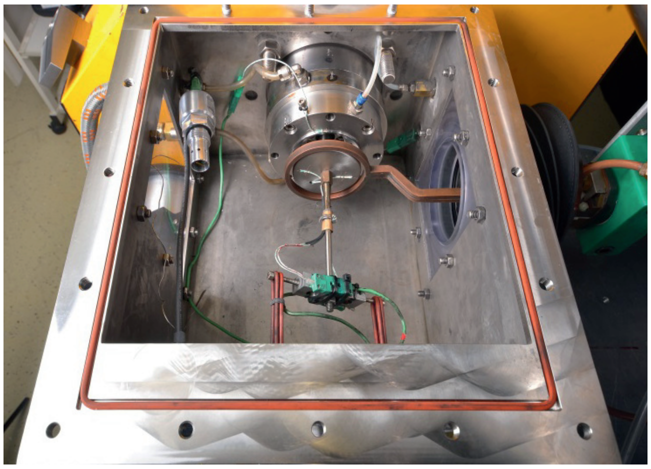


Fig. 10: Top view of the environmental chamber without gasket cover

ENVIRONMENTAL CHAMBER – In order to simulate application-related atmospheres, a special unique environmental chamber was developed to provide extensive temperature testing capabilities under various ambient testing conditions, see Fig. 10.

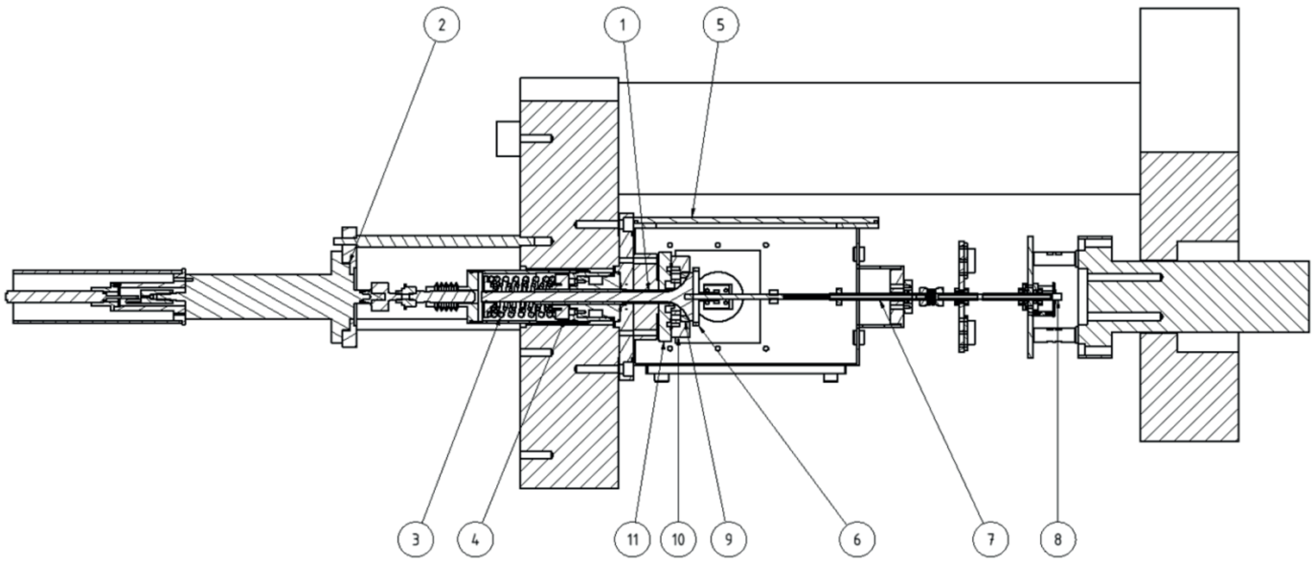


Fig. 9: Schematic of the test rig in test mode I. The parts with numbers are listed in Table 3.

The chamber surrounds the wear pair valve spindle/seat ring and enables a targeted gas flow to simulate exhaust residues. In the first phase, the test can be performed with air, nitrogen, carbon dioxide and water vapor. To validate the gas-tightness a leak test according to DIN EN 1779 was carried out.

TEST MODE I – VALVE CLOSURE - Function of test mode I is to simulate the impact of the valve closing velocity on the wear behavior of the valve and seat ring for an in-depth understanding of the wear mechanisms during valve closure. The valve lift can be varied by the hydraulic cylinder (2) as requested. The typical valve lift applied is 25 mm. An assembly drawing of the test rig is presented in Fig. 9. The test rig consists of 12 systems: 1 – valve; 2 – small hydraulic cylinder; 3 – valve springs; 4 – rotating device; 5 – environmental chamber; 6 – induction coil; 7 – hollow shaft; 8 – slip ring transmitter; 9 – seat ring; 10 – seat ring holder and 11 – cooling flange.

Table 3: Description of test mode I – valve closure

1	Valve sindle
2	Hydraulic cylinder small
3	Valve springs
4	Rotating device
5	Environmental chamber
6	Induction coil
7	Hollow shaft
8	Slip ring transmitter
9	Seat ring
10	Seat ring holder
11	Cooling flange

The hydraulic cylinder (2) actuates the valve spindle (1). Hereby, the valve springs (3) are compressed; valve spindle opens and the rotating device (4) turns the valve spindle. By using a serial established rotating device, it can be granted that the wear-relevant temperature distribution and valve rotation match the real engine operation conditions. To ensure temperature and atmosphere, the environmental chamber (5) is a crucial component. The heating of the valve spindle is realized by an induction coil (6) to heat the valve disc. Auxiliary equipment is passed by laterally arranged socket and a hollow shaft (7). Measurement data acquisition is performed using LabVIEW. In order to control the hydraulic unit, Instron WaveMatrix is used. The seat ring (9) is fixed by conventional press fit into the seat ring holder (10) that is mounted on the cooling flange (11). Hence a constant temperature of the seat ring can be granted.

TEST MODE II – SIMULATION OF PCP - The proposed design was developed to simulate the impact of the PCP on the wear behavior. Depending on a certain frequency the PCP can be investigated in detail. For example, peak combustion pressure up to 220 bar can be simulated at a valve disc diameter of about 90 mm and a frequency of about 8.3 Hz (equal to 1000 rpm). In contrast to test mode I the valve (1) opening is actuated by a compression spring package (3), whereby in the center axis a guide pin is positioned. In order to generate the required forces at relative high frequency using hydraulic actuator, the valve lift works only for decoupling the wear pair. As a result, a conventional rotating device actuated by valve springs cannot be used. Therefore a second hydraulic cylinder (2) is applied to actuate a fixed-connected

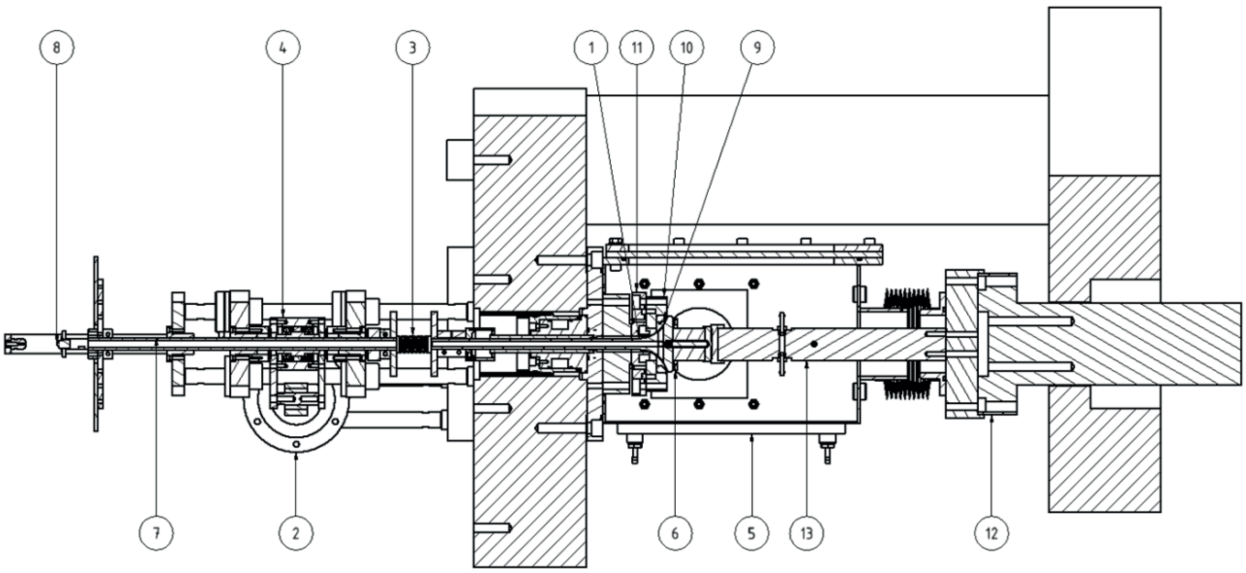


Fig. 11: Schematic of the test rig in test mode II. The parts with numbers are listed in Table 4.

freewheel with a hollow shaft (7) as rotating device. By using of the hollow shaft the rotational motions; however, not the translational motions are transferred to the valve spindle.

Table 4: Description of test mode II – PCP

1	Valve sindle
2	Hydraulic cylinder small
3	Valve springs
4	Rotating device
5	Environmental chamber
6	Induction coil
7	Hollow shaft
8	Slip ring transmitter
9	Seat ring
10	Seat ring holder
11	Cooling flange
12	Hydraulic cylinder large
13	Ram

In a similar manner to test mode I, the gastight environmental chamber (5) is employed. In order to heat and for controlled holding at a defined temperature a smaller induction coil (6) is applied, whereby in the center of the coil a ram (13) transmits the force of the large hydraulic cylinder (12) on the valve face. Components seat ring (9), seat ring holder (10) and cooling flange (11) are the same as those of test mode I. By disconnecting of the small hydraulic cylinder from the freewheel the assembled freewheel and hollow shaft unit can be linearly moved. Hereby, a fine adjustment of the compression spring package and an easy handling of the samples can be obtained. Fig. 11 illustrates the assembled rotation unit of test mode II that is mounted onto the left yoke, whereby the large cylinder (12) is fitted onto the right yoke.

PRELIMINARY RESULTS FROM TESTS WITH THE NOVEL TEST RIG

To investigate the correlation of wear behavior and load parameters, the valve spindles were tested at various temperatures, atmospheres and valve closing velocities. In the first phase, inlet valves were examined. The test temperatures range from room temperature up to 430 °C. In general, temperatures up

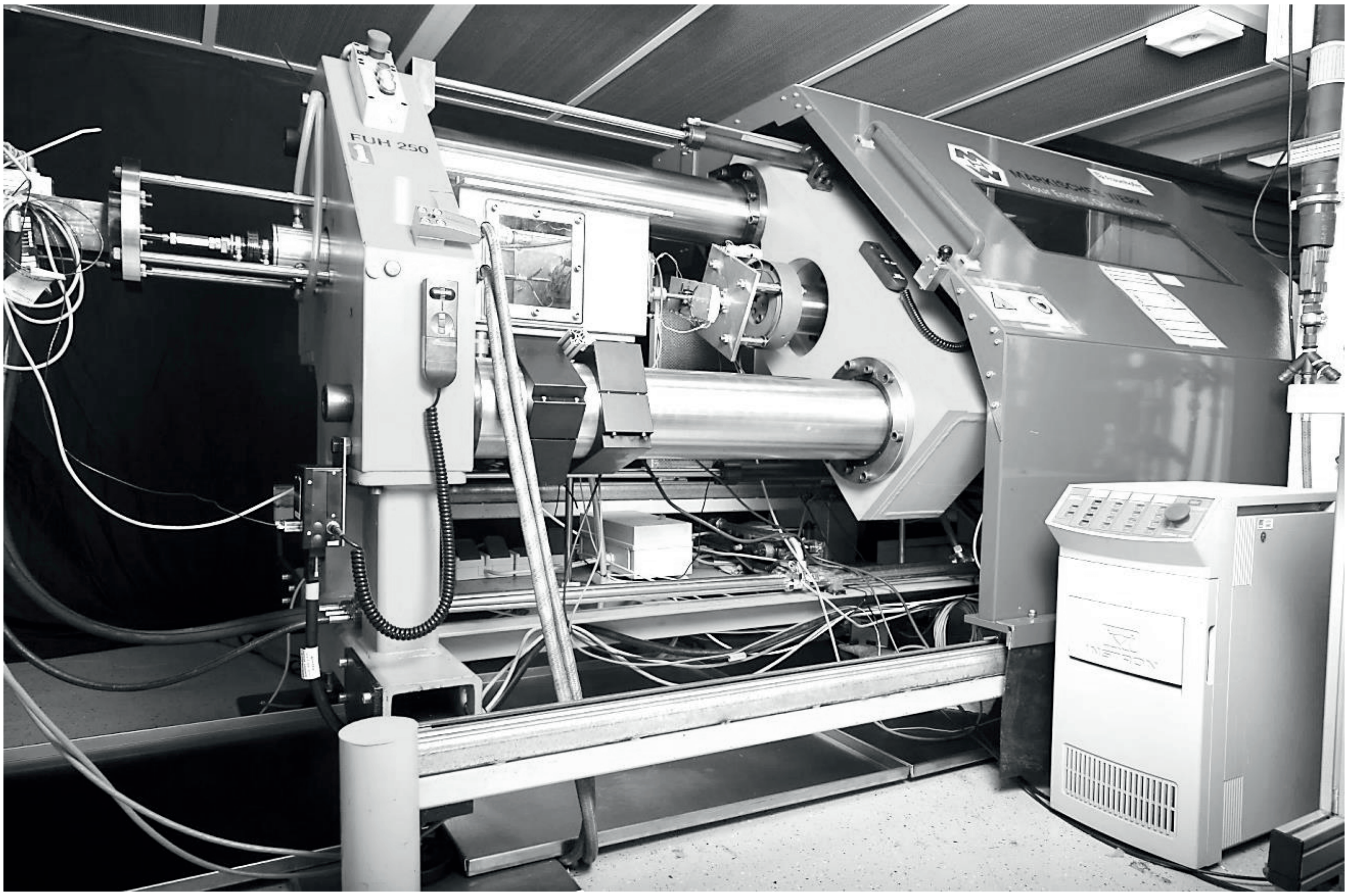


Fig. 12: Valve wear tribometer at Fraunhofer Institute for Mechanics of Materials; equipped for test mode I – valve closure.

to 900 °C can be reached by the heating system. The environmental chamber can be filled with different gases in order to assess the effect of atmosphere on the wear behavior. The closing velocity is controlled by the movement of the hydraulic cylinder and was set to 0.2, 0.6, and 1.2 m/s. Wear pairs were always the same.

EXAMPLES OF RESULTS FROM TEST MODE I (VALVE CLOSURE) – Lifetime of valves in large bore engines are normally several thousands hours. As known, properly working tribological systems show a steady state of wear after running-in. The wear rate changes through the repeated contact process under load and velocity [15]. With regard to efficient testing and to comply large bore engine applications, a testing time of 100 hours was agreed. Three selected samples below serve to illustrate this.

The experiments were interrupted after defined intervals in order to obtain the contour of the valve seating face by profilometry measurements. Thus, the continuous progress of valve wear was tracked. The profile depths plotted against the radial distance from inner diameter to the outer diameter of the seating faces are presented in Fig. 13 and Fig. 15. Comparison of both graphs illustrates the evolution of valve wear at room temperature vs. high temperature (380 °C) while the other conditions (normal air, closing velocity 0.6 m/s) were kept identical. Table 5 shows the test parameters of the presented valves.

Table 5: Test parameters of valves tested in mode I.

	Valve 1 (Fig. 13)	Valve 2 (Fig. 15)	Valve 3 (Fig. 17) – Stress test
Specimen temperature	25 °C	380 °C	450 °C
Surrounding atmosphere	Air	Air	Air
Valve closing velocity	0.6 m/s	0.6 m/s	1.2 m/s
Test duration	100 h	100 h	447 h

Fig. 13 shows the contour of valve 1 that was tested at room temperature. No wear could be quantified at this parameter set. A micrograph of the valve seating surface confirms that the surface becomes only smoother in comparison to the original state which shows grinding grooves, see Fig. 14. This experiment holds as reference for future tests where the parameters will be varied systematically.

Fig. 15 shows clearly the progression of valve wear in the contour plot of the valve seating face at different test durations and at normal operation temperature of 380 °C of an inlet valve. The valve recession after 100 hours is 60 µm almost along the whole radial distance except from the inner diameter where a ligament remains (red arrow) since there is no contact to the seat ring. The contour also shows a small ligament at the outer diameter (green arrow) which can be traced back to the plastically deformed material that is sequentially moved from the contact area to the outer diameter by repeated contact of the valve spindle.

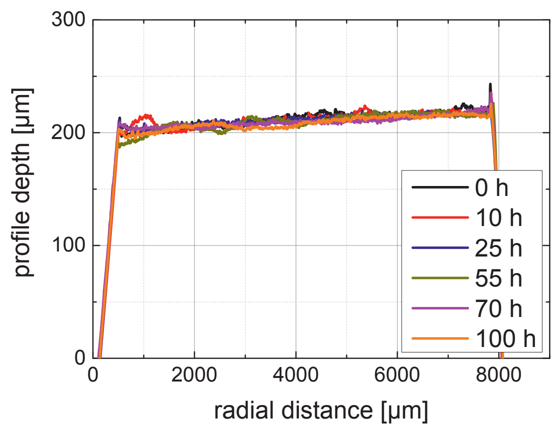


Fig. 13: Valve seat contour measured in time intervals in room temperature test at air and 0.6 m/s. The total test duration is 100 hours.

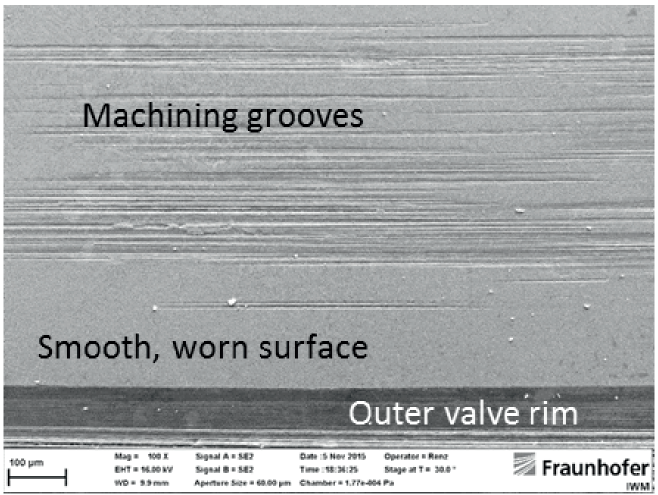


Fig. 14: Surface of valve #1's seating face after 100 hours of testing. Initial contact started at the outer diameter. Testing leads to a smoothening of the surface, where some machining grooves are still visible.

In order to validate the test rig and to subject the wear pair valve spindle/seat ring to extreme conditions, a long-term test was carried out for 447 hours at 450 °C and a high closing velocity of 1.2 m/s at air. Fig. 17 illustrates the contour of the valve seating face before and after this stress test. Severe wear is visible as well as the plastic deformation at the outer diameter (blue arrow), see Fig. 18.

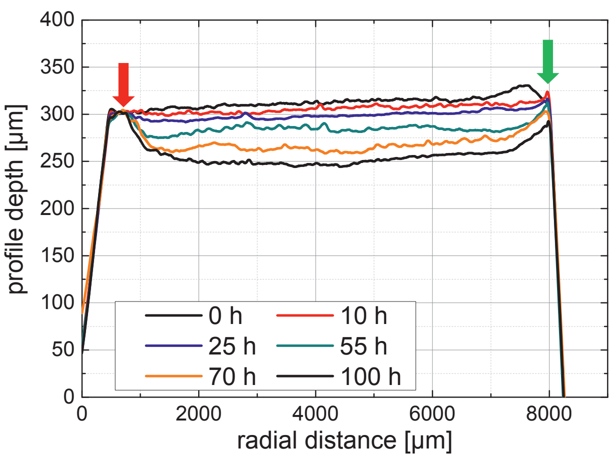


Fig. 15: Valve seat contour measured in time intervals in a high temperature test at 380 °C at air and 0.6 m/s. The total test duration is 100 hours.

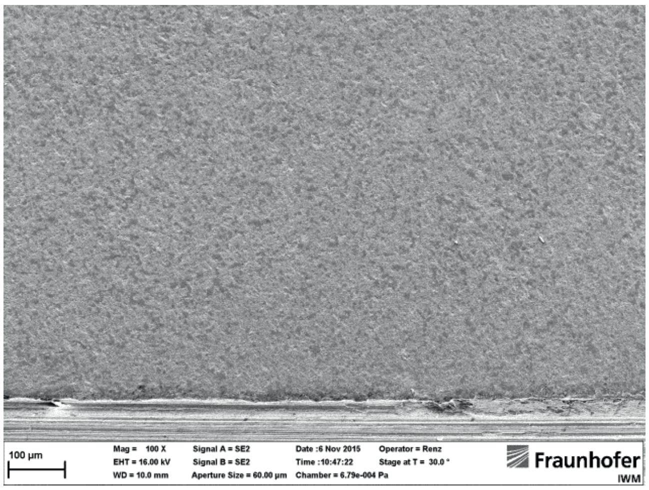


Fig. 16: Surface of the valve #2's seating face after 100 hours of testing. Testing leads to rougher surface that is worn so far that full contact with the seat ring is reached.

From integration of the contour plot and calculation of the rotational volume, the wear rate can be obtained as mm³/h. These values are given in Fig. 19, illustrating the significant impact of the parameters temperature and closing velocity. While the valve at room temperature shows virtually no wear (0.05 mm³/h), the specimen tested at 380 °C shows a roughly 20 times greater wear rate (1.05 mm³/h). The further increase of temperature with additionally higher valve closing velocity results in an excessive wear rate of 3.3 mm³/h.

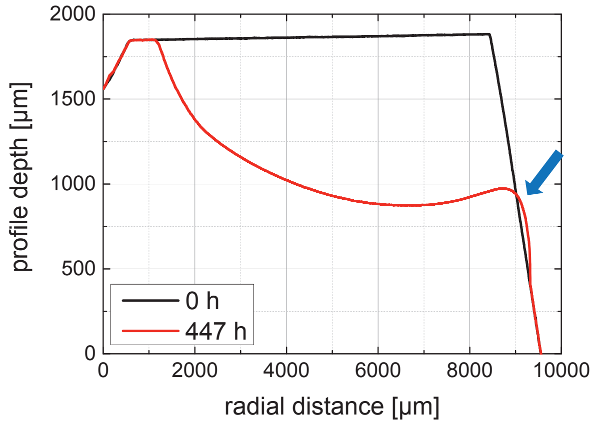


Fig. 17: Valve seat contour measured before and after stress test (450 °C, air, 1.2 m/s closing velocity)

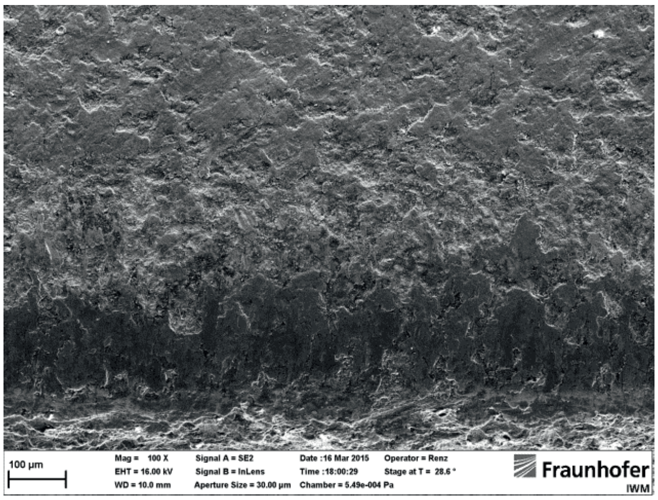


Fig. 18 Surface of the valve #3's seating face after 477 hours of testing. Testing leads to severe wear and a removal of majority of the hardfacing.

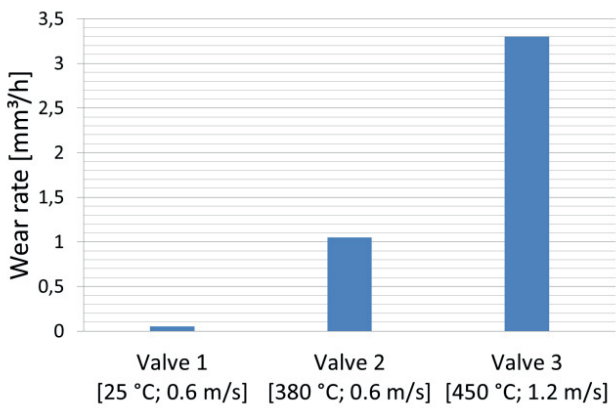


Fig. 19: Wear rates of valves tested in the new test rig.

SUMMARY

The linking between the striving for higher efficiency and global tightening of emissions legislation is one of today's biggest technical challenges in the field of large bore engines. Most of the different approaches have a similar drawback which is higher wear of the components. Especially the wear pair valve spindle and seat ring suffers from high wear when temperatures and PCP rise at the same time as the combustion process becomes cleaner and less oil is available. In order to face this challenge with best matching valve materials and designs, it is necessary to understand the wear mechanisms at the sealing interfaces.

We investigated worn valves made of two different hardfacing alloys that are commercially available and widely used for valves and seat rings in large bore engines applications.

It was found that Stellite® 12 tends to be stronger plastically deformed under shear stress than Tribaloy® T400. This behavior can be traced back to mechanical properties of the matrix and the different microstructure of the hard phases in these alloys. Mechanical properties like elastic modulus at high temperatures and cyclic fatigue behavior under shear stress should be further analyzed in detail. Furthermore, the surrounding atmosphere reacts with the hot material surfaces during operation, leading to formation of oxides as well as oxygen penetration.

The superposition of these various load factors makes it necessary to separate them in the novel designed test rig which is presented in this work. This valve tribometer allows full control of test parameters which are usually interdependent in engine tests. Especially the two test modes – valve closure and PCP – provide discrete control to the mechanical loads which depend on valve train dynamics and PCP in real engines.

The first results already allow an evaluation of temperature and valve closing velocity in test mode I. Comparison of tests at room temperature and 380 °C pointed out a strong impact of the thermal load. The stress test over 447 hours at 450 °C with a closing velocity of 1.2 m/s proved the feasibility of the test rig and illustrated furthermore the limits of Stellite® 12. The measured linear wear rate of 2.2 µm/h is of the same magnitude as for the excessively worn valve from engine test (3.6 µm/h). Hence the test rig has proven able to produce wear rates those found in engine tests. Consequently, it establishes a research tool for study the wear mechanisms of valve closure and PCP in detail in a sustainable way.

Whether long-term tests or only single cycle test the novel valve wear tribometer for large bore engines is an unique test rig to acquire new knowledge about the wear mechanisms of valve closure and PCP. Thereby hopefully, a sustainable approach can be given to minimize valve wear in highly efficient and low-emission large bore gas engines running on natural gas.

OUTLOOK

Systematic parameter studies in conjunction with latest lab surface analysis will provide a better in-depth understanding of wear processes and crucial factors that have to be considered by the choice and development of materials and future design philosophy of valve spindles in large bore gas engines.

REFERENCES

[1] LEHMANN O., SCHERGE M. and RENZ A.: „Wear mechanism study of Stellite®-hardfcaed combustion inlet valve spindles in lean-burn large bore gas engines“, 9th Dessauer Gas Engine Conference, 2015, pp. 137-145

[2] GILES W.: "Valve Problems with Lead Free Gasoline", SAE paper no. 710368, 1971, pp. 1475-1483

[3] GODFREY D. and COURTNEY R.L.: "Investigation of the Mechanism of Exhaust Valve Seat Wear in Engines Run on Unleaded Gasoline", SAE paper no. 710356, 1971, pp. 1449-1454

[4] MALATESTA M.J., BARBER G.C., LARSON J.M. and NARASIMHAN S.L.: "Development of a Laboratory Bench Test to Simulate Seat Wear of Engine Poppet Valves", Tribology Transactions 36, 1993, pp. 627-632

[5] WANG Y.S., NARASIMHAN S., LARSON J.M., LARSON J.E. and BARBER G.C.: "The effect of operating conditions on heavy duty engine valve seat wear", WEAR 201, 1996, pp.15-25

[6] LEWIS R., DWYER-JOYCE R.S. and JOSEY G.: "Design and Development of a Bench Test-Rig for Investigating Diesel Engine Inlet Valve and Seat Insert Wear", The Institution of Engineers Australia, Austrib `98 – Tribology at Work, Brisbane 6-9 December 1998

[7] US 6,647,770 B2 Apparatus and method for testing internal combustion engine valves, November 18, 2003

[8] CHUN K.J., KIM J.H. and HONG J.S.: "A study of exhaust valve and seat insert wear depending on cycle numbers", WEAR 263, 2007, pp. 1147-1157

[9] SLATTER T., TAYLOR H., LEWIS R. and KING P.: "The influence of laser hardening on wear in the valve and valve seat contact", Wear 267, 2009, pp. 797-806

[10] FORSBERG P., GUSTAVSSON F., HOLLMAN P. and JACOBSON S.: "Comparison and analysis of protective tribofilms found on heavy duty exhaust valves from field and made in a test rig", WEAR 302, 2013, pp. 1351-1359

[11] MASCARENHAS L.A.B., GOMES J.d.O., BEAL V.E., PORTELA A.T., FERREIRA C.V., BARBOSA C.A.: "Design and operation of a high temperature wear test apparatus for automotive valve materials", WEAR 342-343, 2015, pp.129-137

[12] RAMALHO A., KAPSA P., BOUVARD G., ABRY J.-C. and YOSHIDA T.: "Effect of temperatures up to 400 °C on the impact-sliding of valve-seat contacts", WEAR 267, 2009, pp. 777-780

[13] OOTANI T., YAHATA N., FUJIKI A. and EHIRA A.: "Impact wear characteristics of engine valve and valve seat insert materials at high temperature (impact wear tests of austenitic heat-resistant steel SUH36 against Fe-base sintered alloy using plane specimens)", WEAR 188, 1995, pp. 175-184

[14] WEI M.X., WANG S.Q., ZHAO Y.T., CHEN K.M. and CUI X.H.: "Wear Behavior and Mechanism of a Cr-Mo-V Cast Hot-Working Die Steel", Metallurgical and Materials Transactions 42A, 2011, pp. 1646-1656

[15] STACHOWIAK G.W.: "Wear – Materials, Mechanisms and Practice", John Wiley & Sons Ltd, 2006, ISBN-13: 978-0-470-01628-2

[16] FORSBERG P.: "Combustion Valve Wear – A Tribological Study of Combustion Valve Sealing Interfaces", Doctoral thesis, Uppsala University Sweden, Department of Engineering Sciences, 2013

[17] CAMERON C.B.: "TRIBALOY Intermetallic Materials: New Wear- and Corrosion-Resistant Alloys"; COBALT 1974 3, 1974, pp.49-53

[18] SATO K., MIDORIKAWA T., TAKAHASHI T., OSHIGE H.: "Development of Valve Seat Material for Gas-Fueled Engines"; SAE Technical Paper 2000-01-0911, 2000

CONTACT

Corresponding author: Oliver Lehmann
Märkisches Werk Halver GmbH
Phone: +49 (0) 2353 917 203,
E-mail address: o.lehmann@mwh.de
Internet: www.mwh.de

Co-Author: PhD Alexander Renz
Fraunhofer Institute for Mechanics of Materials IWM
Internet: www.iwm.fraunhofer.de

MÄRKISCHES WERK

Your Engine. Our Ingenuity.™

Märkisches Werk GmbH

Haus Heide 21
58553 Halver, Germany
Phone: + 49 - 2353 - 917 - 0
Email: info@mwh.de

MWH Americas
americas@mwh.de

MWH China
china@mwh.de

MWH Japan
japan@mwh.de

MWH Singapore
singapore@mwh.de