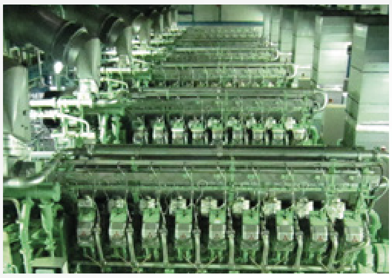
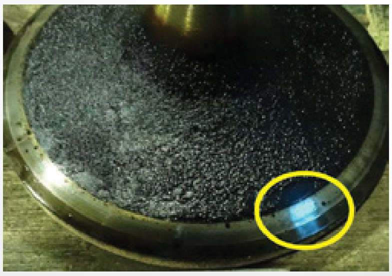
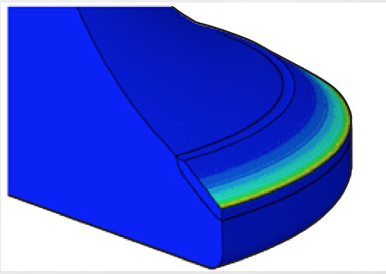
Long-Term Field Study of Valve Wear

Paper courtesy of 7th Rostock Large Engine Symposium


From severe wear to a lifetime of 32,000 running hours
Field study on valve spindles in lean-burn gas engines

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From severe wear to a lifetime of 32,000 running hours: Field study on valve spindles in lean-burn gas engines

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Abstract

Besides modern engine concepts resulting from tightening emission legislations, robustness in operation is key for the future of large bore engines. Motivated by the Paris and Glasgow climate agreements, today's engine developments shall entail the ambitious transition from carbon-based fossil fuels to carbon-neutral or zero-carbon fuels. The reliability of engine components is of essential importance in this context. In particular, gas exchange valves are in focus as they face highest thermal, mechanical and corrosive loads.

This work deals with a development of the tribological pair valve spindle/seat ring, which started at the analysis of severe valve wear and ended at a running time of 32,000 hours of newly designed components in the engine field. The field study comprises several valve designs which were tested on a constantly operated lean-burn gas engine (6 MW, 750rpm). Theoretical and experimental findings from recent years, which provided detailed insight into the tribosystem valve spindle/seat rings, triggered the material choice and material-related design. Both valve spindle and seat ring were regulary investigated at 4,000-hour intervals from the beginning of the test. Measurements of static valve lash as well as visual, geometrical and microscopical investigations were done to assess the wear behavior. Moreover, the engine performance was recorded to understand the impact of valve spindle and seat ring geometries on the intake manifold airflow.

The results reveal that the material, geometry, manufacturing process and load collective are key factors to mitigate the risk of severe valve wear. The field study demonstrates that a valve recession rate below 10 nm/hr on a large-bore gas engine is possible, thus enabling a valve lifetime of minimum 32,000 running hours. Furthermore, the design of the valve seating face (seat angle and seat width) affects the cylinder filling volume and contributes to improving the thermal efficiency of the engine.

This field study supports and complements latest material and tribological research on model and component scale. The analysis of dominating valve wear mechanisms, the individual material choice and adequate manufacturing processes contribute to increasing lifetime without losses of thermodynamic efficiency, thus securing engine reliability and robustness at increasingly drier operating conditions.

1. Introduction

Market- and operation-related boundary conditions increasingly require flexible solutions for large-bore engines, while the legislative framework leads to a phase out of conventional solutions in the long run. However, large bore engines still play a major role for power generation or propulsion in marine and locomotive today, but undergo new operation mode and fuel type developments to increase efficiency, reduce emissions and provide operation flexibility [1][2]. In this context, the impact of engine performance upgrades on the wear pair valve spindle/seat ring are widely discussed [3]. Whether or not, and to which extent a detrimental impact must be expected, is of highest interest to engine builders [4].

The lean-burn combustion concept is a well-known emission reduction measure for large bore gas engines to reduce nitrogen oxides. Due to the change to overstoichiometric air-fuel ratio, less combustion residues are provided to form a wear-protective tribofilm on valve seating faces. Forsberg et al. [5] showed that a wear-protective tribofilm is necessary to get ultra-mild wear, along with long component lifetimes. Soot as one of these combustion residues has ambivalent properties, which was discussed from different perspectives. Rounds [6][7] showed that soot is not abrasive but adsorb anti-wear additives, thus diminishing anti-wear properties. Ryason et al. [8], however, concluded that soot particles are abrasive because they were found to generate grooves and breakouts in metallic surfaces. Antusch et al. [9] investigated that the significant effect of combustion residues on wear depends more on the mechano-chemical reaction than on soot morphology, surface chemistry and reactivity of the particulate species. Soejima et al. [10], Yamaguchi et al. [11] and Aldajah et al. [12] found that soot particles reduces the thickness and extension of wear-protective tribofilms and are abrasive. Truhan et al. [13] concluded that the chemical activity of combustion residues and their reaction with phosphate compounds prevents the formation of liquid boundary layers on metal surfaces. The publications mentioned contain partially contradictionary, incomplete concepts and explanations about effects on valve wear.

Lehmann et al. [14] showed that valve seating faces based on Stellite-alloys provide a low wear-resistance, particularly on lean-burn gas engines. Renz et al. [15] concluded that metallic oxides have the potential to replace wear-protective tribofilms fully formed by combustion residues. Rather than quick-fix solutions, well-found solutions based on materials and designs suitable for the individual engine architecture are required. Starting from the development of a unique test rig in 2016 [16], Märkisches Werk developed new wear-resistant metal matrix composite alloys for both seating faces of valve spindle and seat ring [17].

This paper proves the potential of metal matrix composite alloy to extend lifetime to 32,000 running hours without loss of engine output. The material-based design was validated in a field study on the KU Gas engine by Mitsubishi Heavy Industries Engine and Turbocharger, Ltd. (MHIET) [18][19].

2. Case study: Field test through 32,000 operating hours

2.1. Test target

The described case study was carried out on a MHIET KU Gas engine, a large bore gas engine with 300 mm bore and a power of 320 kW/cyl (Table 1). The KU Gas engine series is being developed aiming for both high efficiency and reliability of components.

Engine Type	Unit	KU30GA	KU30GSI	KU30GSI-Plus
Ignition		Micro Pilot	Spark Ignition	
Cylinder Count		12-18		
Bore and Stroke	mm	300 x 380		
Engine Speed	min^{-1}	720 / 750		
Power Output	kW	3,650 – 5,750		
Electrical Efficiency	%	46.0	46.5	49.5
NOx (O_2=0%)	ppm	<200	<320	
Engine Weight	ton	40-60		

Notes:
1. Electrical efficiency at generator termina, including driven pump.
2. Based on ISO 3046 conditions with 5% allowed tolerance.
3. Methane Number 65
4. Fuel Quality conforms to MHI Fuel SPEC

Table 1: Main technical data of Mitsubishi KU Gas engine series [20][21]

The KU Gas engines series operates at an advanced Miller cycle timing and a reduced lubrication oil consumption (LOC) due to the optimized piston ring configuration.

MHIET strives to develop highly sustainable engines with minimum service and maintenance efforts, which includes the cylinder head component systems. The target lifetime of valve spindle and seat ring is minimum 16,000 operating hours without interim servicing or reconditioning of the parts.

Figure 1: Example of MHIET KU Gas engine power plant

2.2. Valve wear

Generally, all KU Gas engines are equipped with the same intake valve spindle and seat ring designs. Along with increased peak combustion pressure, the newly introduced reduced oil consumption led to higher valve wear and premature failures. In few cases, severe wear on the valve spindle occurred, which was usually recognized and investigated during regular maintenance overhaul at intervals of 4,000 operation hours. The valve spindle in Figure 2 indicates the position of a severely worn valve spindle on which a microscopic investigation was made. Figure 3 shows the cross-sectional cut with clearly visible valve wear highlighted by the yellow line.

Figure 2: KU Gas engine intake valve after 4,000 operating hours

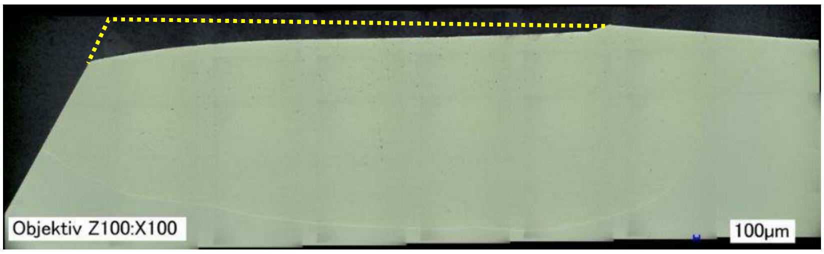

Figure 3: Cross-sectional cut on intake valve spindle after 4,000 operating hours (position: refer to Figure 2)

The micrograph in Figure 3 indicates the loss of volume on the valve seating face. The wear scar on seat ring and valve spindle forms an annular shape with a width of approx. 7.64mm, which is the maximum possible contact area between both components. A broad investigation on all valve spindles of an 18-cylinder engine confirms this phenomenon, but also shows that the contact pressure on the seating surface is not equally distributed. Exemplarily, Figure 4 compares two intake valve spindles from the same cylinder with a full contact, proven by the highlighted reflection (yellow circles). The seating faces show a small band of a black layer, which accounts for an oil or ash surface layer. This indicates a higher surface pressure on the outer diameter (B6-3), respectively on the inner diameter (B6-4) of the seating face.

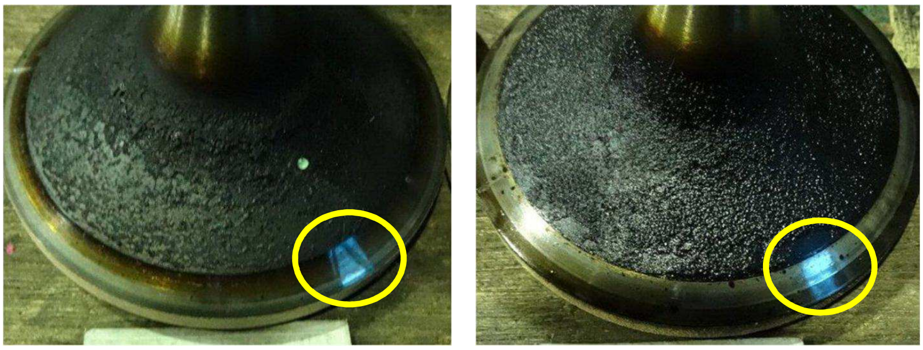

Figure 4: Valve spindles from KU Gas engine after 4,000 operating hours, taken from cylinder B6-3 (left) and B6-4 (right)

The valve recession shown in Figure 2 is about 0.8mm after 4,000 operating hours[1]. Equation (1) shows a wear rate above 200nm/hr which is above the area of mild wear [22]. Statistically, the wear rates vary from cylinder to cylinder. Both the wear rate and the statistical variations do not comply to the the MWH best practice design for valve spindle.

$$wear\ rate = \frac{valve\ recession\ on\ component}{running\ hours} = \frac{838{,}000nm}{4{,}000hr} = 209.5\ \frac{nm}{hr} \qquad (1)$$

[1] The exact wear amount could not be measured, but a comparison of the nominal original geometry with the microscopically investigated seat geometry returned a valve recession of 0.838mm.

Prior to finding a well-founded solution, the actual load collective and tribological system was analyzed following a systemic approach. This systemic approach comprises thermal, chemical and mechanical loads, such as temperature distribution, corrosion or stress calculation.

The tribologically induced surface layers of both valve spindle and seat ring (Figure 5 and Figure 6) give insight into the present wear modes and material answer.

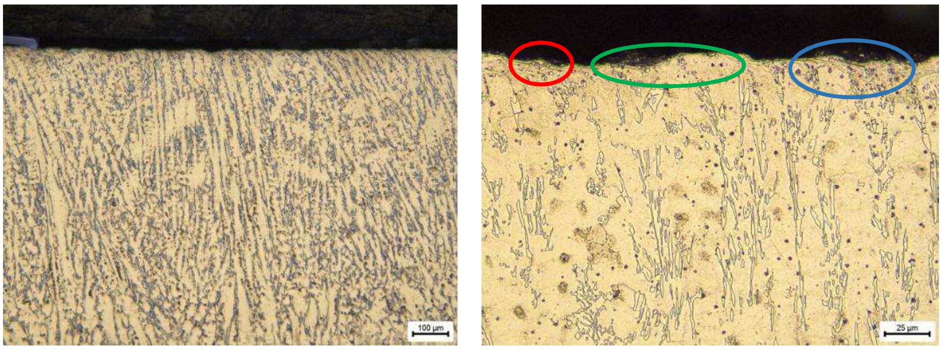

Figure 5: Cross-sectional cut of valve spindle seating surface

The valve seating face is hardfaced with a nickel-based alloy with carbidic silicide hard phases embedded in nickel-chromium solid solution. Based on the phenomena visible in the detailed microscopic view in Figure 5, surface fatigue is considered to be the dominant valve wear mechanism. This wear mode leads to typical delamination of wear particles, based on three different stages:

- Shear-stress in microstructure (red circle)
  High mechanical loads such as high surface impacts lead to shear stresses in the surface-near areas. Less ductile and high-chrome phases may crack.

- Mechanical mixing (blue circle)
  The valve seating face material, but probably also surface oxides, combustion residues and/or seat ring particles are mixed and compacted.

- Surface delamination (green circle)
  Eventually, surface particles spall off, supported by the sliding distance between valve spindle and seat ring.

Based on the findings, the mechanical impact on the tribosystem valve spindle/seat ring exceeds the material capability. Corrosion is not visible.

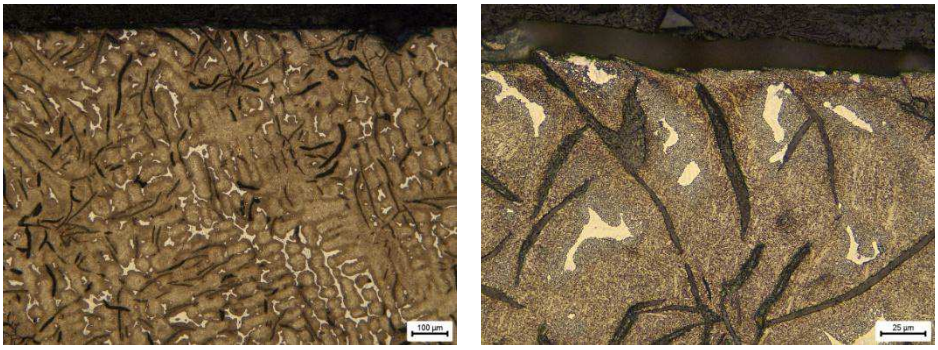

Figure 6: Cross-sectional cut of seat ring surface

Figure 6 shows the surface-near area of the seat ring, which is made of a lamellar cast material. The surface is damaged by spalling formation.

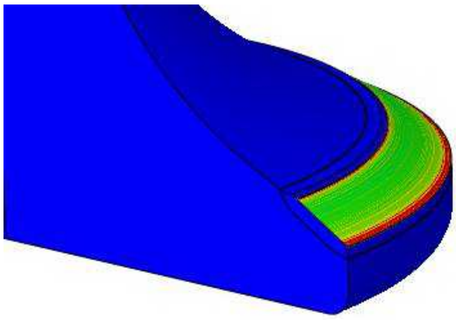

Figure 7: Contact situation between valve spindle and seat ring

Further analyses are made to understand the load collective, such as contact situation between valve spindle and seat ring (Figure 7). A defined contact is important to reach a steady state wear, which is not the case on the current parts. The finite-element analysis applied proves that the whole valve seating face contacts the seat ring. Additionally, manufacturing tolerances may significantly change the surface pressure distribution along the seating face.

2.3. Solution approach

Prior to finding a well-founded solution, the load collective and dominant valve wear mechanism was analyzed. As valve wear is a system property, the solution comprises holistic counter-measures rather than quick-fix adjustments.

The new design for both valve spindle and seat ring is based upon past test and validation experiences [14] at Märkisches Werk and tries to approach all relevant aspects of the MHIET KU Gas engine tribological system. In order to convert the present tribological system to ultra-mild wear condition, the following aspects were considered.

Materials

The main requirements of the valve spindle and seat ring material are its capability to dissipate friction energy. Furthermore, the material should provide corrosion resistance while providing mechanical strength at elevated temperatures, without chemically interacting with one another.

The system solution consists of a Stellite 12 alloy hardfacing on the valve seating face (Figure 8). This cobalt-based alloy has a characteristic dendritical microstructure if it is produced at close process parameter control. The structure of the matrix-embedded carbidic hard phases effectively provides the high temperature wear resistance, in particular the cobalt-chromium matrix to absorb the impact energy, while at the same time protecting the surface from surface fatigue up to highest mechanical loads. In the harsh engine atmosphere, Stellite 12 provides highest corrosion resistance.

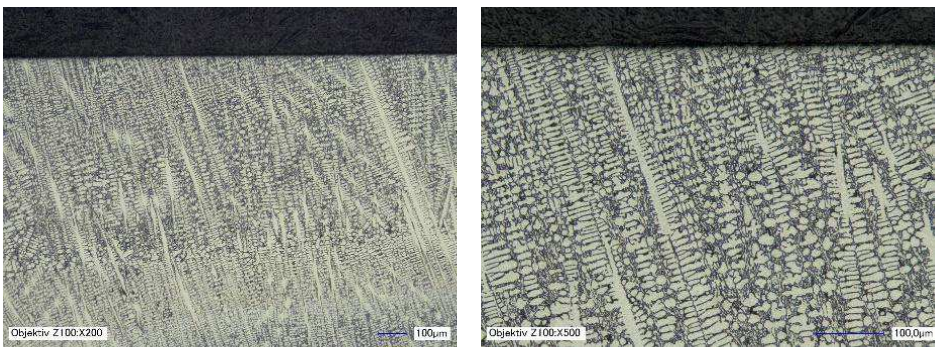

Figure 8: Cross-sectional cut of valve spindle seating material: Stellite 12

The seat ring seating face was changed from solid to hardfaced surface. Thus, a cost-effective base material with higher thermal conductivity could be applied. The hardfacing material is the proprietary Märkisches Werk material MW-H5428-8 (Figure 9). Like the valve spindle hardfacing, this material is a cobalt-based alloy but containing intermetallic phases in a different morphology.

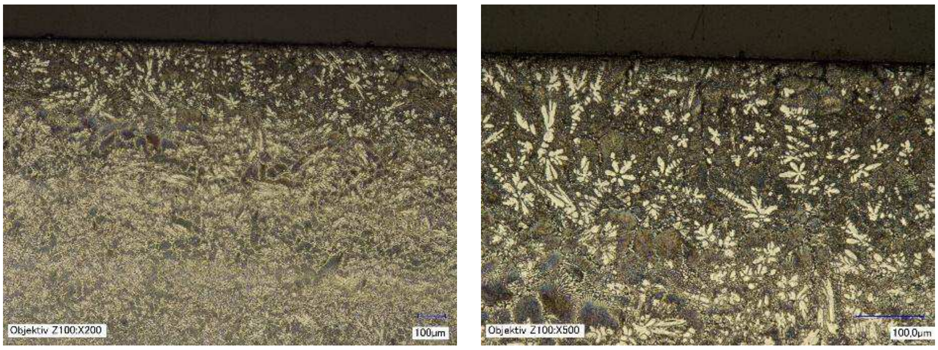

Figure 9: Cross-sectional cut of valve spindle seating material: MW-H5428-8

Geometrics

The geometry of the overall valve train system affects the tribological pairing valve spindle and seat ring. From a tribological standpoint, the contact area, contact pressure and relative movement between the contact partners are important.

The seating angle geometry affects the intake air flow. The higher the air flow deflection, the higher are air flow losses. A small seating angle (Figure 10) causes a high flow deflection, thus high flow losses, whereas the sliding distance between the contact partners is reduced.

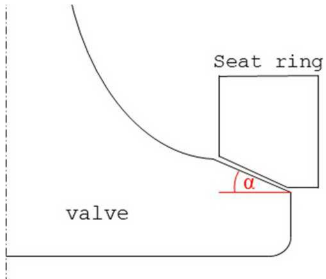

Figure 10: seating angle α on valve spindle and seat ring

The contact position and pressure is calculated with finite-element analysis and seating angle nominal values and tolerances set to a value which ensures a defined contact between valve spindle and seat ring on the outer diameter position. The distribution of the surface pressure will have its peak on the outer diameter of the seating faces (Figure 11). Manufacturing tolerances are set to keep this pressure distribution.

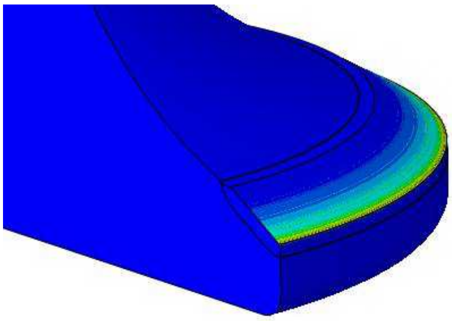

Figure 11: Contact surface pressure on the valve spindle after finite-element optimization

The combustion stroke generates a pressure load at the bottom of the closed valve. This causes an elastic deflection of the whole valve head in vertical direction. The total maximum displacement is approximately 30 µm in the center of the valve spindle. The local displacement in the contact plane is the wear-relevant micro-sliding and has to be selected depending on materials and application. The larger the seating face angle, the higher is the displacement vector, in return leading to wear. In addition to this, greater micro-sliding distances tend to form more stick-slip-effects, which aggravates the wear behavior of the contact pairing. On the opposite, smaller seating angles cause reduced micro-sliding distances.

As the wear rate on the previous component design indicates a high load collective, it was questionable whether a system with 30° seating angle could provide ultra-mild wear. In order to mitigate the risk, a second configuration with 20° seating angle version was designed in parallel. Both the 20° and 30° seating angle configuration have otherwise similar properties.

2.4. Field test execution

The solution systems comprising two configurations were installed on an MHIET KU Gas engine in Japan, which is in stationary operation mode with constant load and which could be accessed anytime. Whilst the engine was running at constant speed and load, the test objects were reviewed after intervals of approximately 4,000 operation hours.

The cylinder head was disassembled after each 4,000 operation hours (test plan in Figure 12) and the valve spindles and seat rings were dismounted for destructive testing and investigation. The engine performance record, the operating conditions and observation results immediately after disassembling the cylinder head were obtained by MHIET.

The most significant parameter for valve wear is the overall valve recession and is regularly measured on the gap between valve spindle tip end and valve connector bridge. In the field study though, the valve recession was measured directly on the valve seating surface at an interval of 4,000 operating hours by profilometric measurements.

The engine information and operating data were evaluated and thoroughly analysed by MHIET, whilst the detailed component investigation was done at Märkisches Werk, focusing on the seating contact between both components and followed a standard routine to ensure compatibility:

- Visual inspection of the components
- Multiple macroscopic and microscopical records of the seating surface at each 90° offset
- Cross-sectional cut and microscopic records of the surface-near, etched microstructure at the positions inner, mean and outer seating face diameter
- Profilometric measurements of all seating faces

Further investigations were carried out as needed.

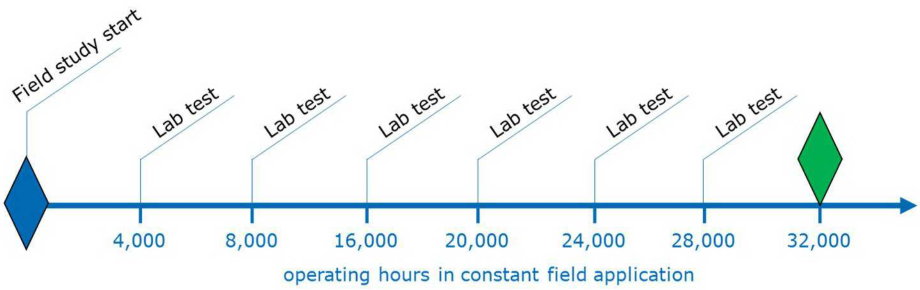

Figure 12: Test plan for field study KU Gas engine

3. Results

The field validation of the valve component system generally passed without major incidents. The field engines operated at relatively constant operation parameters without any significant operation mode changes, thus the results are interchangeably comparable between the test stages.

Valve recession

On both seating angle configurations, the valve wear remained on a low level with a valve wear rate constantly below 20nm/hour which can be classified as ultra-mild wear. Figure 13 summarizes the wear recession in a comparative graph. The 20° seating angle version test was stopped at a lifetime of 20,000 operating hours due to engine performance fluctuations.

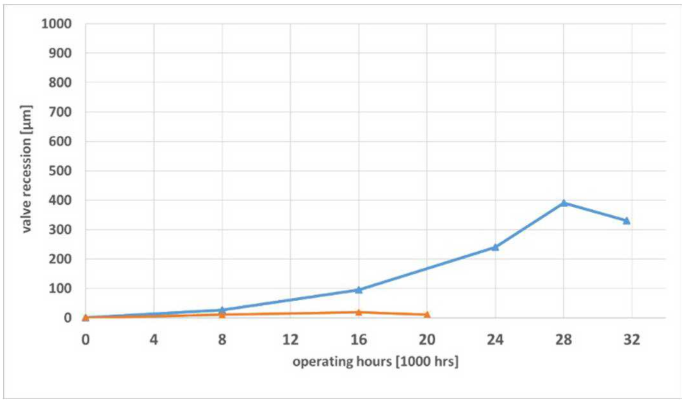

Figure 13: valve recession diagram

The field study ended at 32,000 operating hours at a total valve recession of less than 500µm. From a valve wear perspective, the 20° seating angle configuration was slightly advantageous against the 30° seating angle configuration, yet valve wear on both configurations is on an ultra-mild wear level.

Engine performance

As presumed during the geometrical design evaluation, the 30° seating angle configuration did perform well with respect to electrical efficiency of the gas engine. The engine output is constantly available without any significant drifts.

The 20° seat angle configuration yet led to some engine performance fluctuation. It is estimated that the pressure loss of the 20° seating angle valve spindle affected the air supply. Even though the efficiency gap was very slight, the 20° seating angle configuration test was ended at 20,000 operation hours and only the 30° seating angle configuration proceeded to the test time of 32,000 operation hours.

Materials

The destructive testing of valve spindles and seat rings was done at every test interval. A cross-sectional cut of the seating face was taken from the outer seating diameter on both components. The segments taken after 24,000 operation hours (Figure 14 and Figure 15), which exemplarily represent the investigation results throughout the whole field study, feature typical material characteristics in the microstructure.

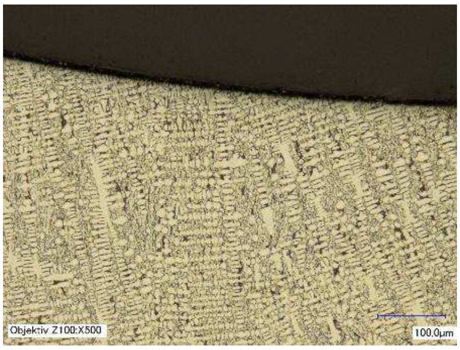

Figure 14: L6-3 valve spindle, 24,000 hours

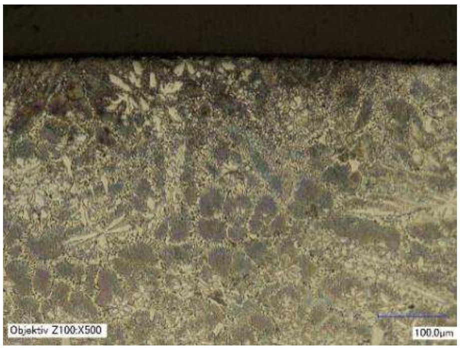

Figure 15: L6-3 seat ring, 24,000 hours

The surface-near zone has a comparable appearance between all levels of usage. A wear-protective tribofilm is not visible on the micrographs. There are no indicators for wear appearances like spalling, high plastical deformation or gradients, adhesion, delamination or corrosion effects.

The close-up of the valve spindle seating face (Figure 14) is characterized by the typical microstructure of Stellite 12. The evolution of the dendritic structure is an outcome of a tailor-made welding process with close process control to match specific material heat treatment requirements.

Many investigated seat rings (Figure 15) do still show turning marks on their seating face which indicates a wear rate below the valve spindle wear rate. This is beneficial for the engine maintenance effort as the component is not subject to early exchange, which is more extensive than exchanging a valve spindle. The microstructure of embedded intermetallic phases in the metal matrix is characteristic for MW-H5428-8 alloy with its good impact energy dissipation, but also its resistance against shearing forces and tribochemical corrosion.

Geometrics

The geometrical design comprises various features which are part of the solution system. Besides the stress calculation at peak load and the design of the functional pairing valve spindle / valve guide, the contact interface between valve spindle and seat ring is key for the system solution.

The initial contact area of valve spindle and seat ring is on the outer diameter of the seating face with a defined, small difference angle between the two seating faces. The contacting area of the tribological faces increases under peak combustion load, causing the valve head to deflect along the vertical axis, thus diminishing the difference angle between the seating faces.

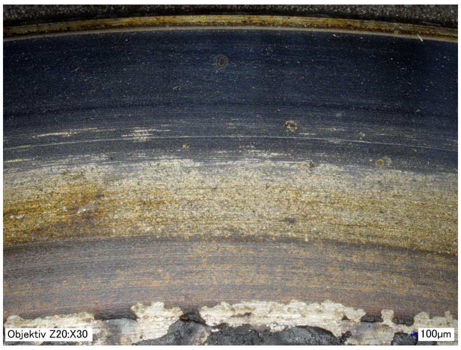

Figure 16: L7-4 valve spindle seating top view, 8,000 hours

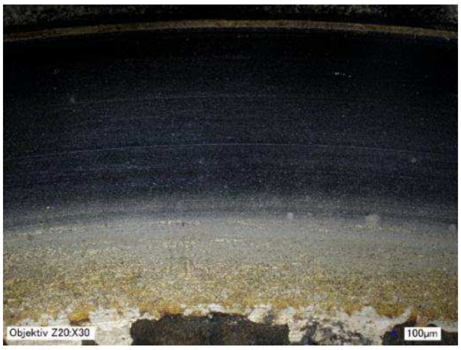

Figure 17: L2-4 valve spindle seating top view, 16,000 hours

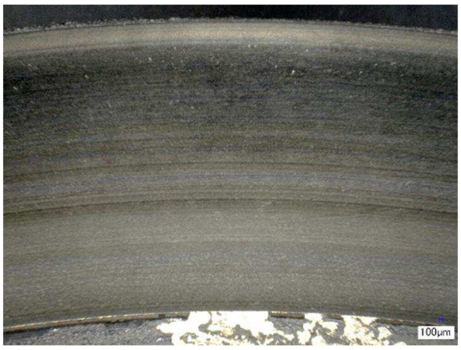

Figure 18: L6-3 valve spindle seating top view, 24,000 hours

Figure 19: L8-3 valve spindle seating top view, 32,000 hours

Several valve sets were tested during this field study to substantiate the statistical evidence. The valve spindle and seat ring contact zone can be assessed in Figure 16 through Figure 19. The valve contacting area is progressing with the operation hours from approximately 55% to 100% contacting area.

The profilometric measurement after 16,000 operation hours (Figure 20) proves evidence of the optical macroscopic surface inspection (Figure 17).

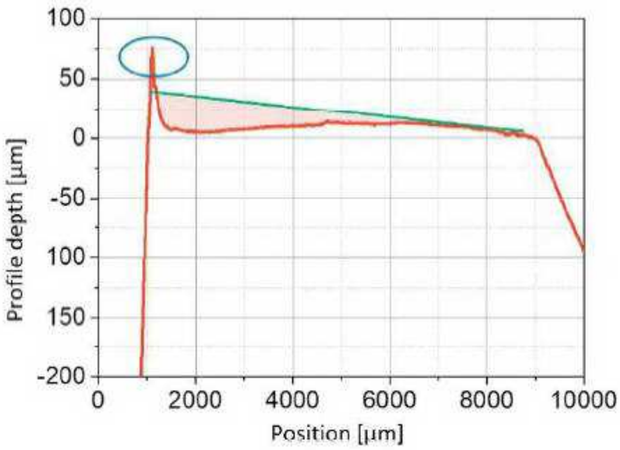

Figure 20: Profilometric measurement on L2-4 valve spindle seating face, 16,000 hours

The green line indicates the original contour of the seating face. The red line is the actual surface profile. The difference between the two lines (bright red zone) is the worn area and protrudes to approximately 70% of the seating width. The peak on the left graph side (blue circle) is an artefact from measurements, possibly triggered by some combustion residues on the part.

4. Discussion

Valve spindle and seat ring designs, which worked well in past engine setups, are not able to meet actual requirements of the MHIET KU Gas engine series. The harsh component environment due to the lean-burn concept with increased peak firing pressure and reduced lubrication oil significantly reduces the component lifetime. Starting from this problem, Märkisches Werk carried out extensive research of valve wear on large bore engines as a limiting factor for component lifetime and introduced a metal-matrix composite alloy, which was validated in a field study through 32,000 operating hours.

The field study started with two design configurations with different seating angles. Both configurations provided comparable wear rates, though one configuration was stopped at 20,000 operating hours because the engine performance could not reach the desired stability. The field study was completed with the other configuration with high engine performance stability. Regular investigations on valve spindles and seat rings showed evidence of an ultra-mild wear rate, providing a validated lifetime of 32,000 operating hours.

Key to finding a well-found solution is understanding valve wear as inherent to a tribological system comprising a load collective, materials, component design and other contributing factors. However, materials are significantly contributing to the wear system and provide insight into the dominant valve wear mechanism. The chosen valve and seat ring material, namely metal-matrix composite alloys of specific chemical composition and morphology, was chosen with regard to the load collective applied. Previous wear mechanisms could thus be overcome. Providing a defined seating pressure distribution is important to establish a steady state wear situation. The geometrical design, proven by finite-element analyses, contributed to the constantly ultra-mild wear rate.

The field study results were transferred into the regular engine and maintenance specification. Reduced maintenance services and a reduced risk of premature failure provide significant advantages for the engine operator, but also contributes to a reduction of operational expenses.

Prolonging valve spindle and seat ring lifetime fits into the long-time plan by MHIET to reduce plant operation cost and provide engine solutions which contribute to emission reduction and efficiency increase [21]. Besides the valve train components, an optimized piston, piston ring pack and cylinder liner design enhanced the necessary maintenance intervals. The crank pin bearing material was changed to a design with improved longevity. Furthermore, MHIET continuously improved the combustion system from micro-pilot injection to a spark-ignited solution, which further stabilizes both engine efficiency and thermo-management of the engine.

While Märkisches Werk provides well-found solutions for the technical issue valve wear, new fuel types will change the tribological system. With hydrogen, ammonia and methanol as promising future fuel types, the implications on the wear pairing valve spindle/seat ring are yet unclear. Märkisches Werk carries out basic research on valve materials and tribology with regard to future fuels and develops technical solutions for future engine concepts.

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