Making Valve Wear Predictable

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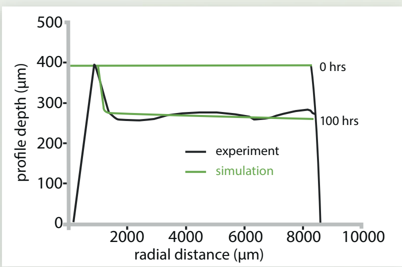
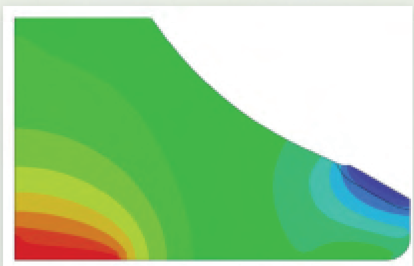
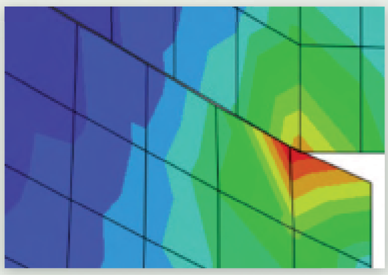
The Most Precise Lifetime Simulation







Cutting-Edge Wear Simulation → Enable Optimal Lifetime → Empower Your Future Engine

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1 INTRODUCTION

The public debate about climate-neutral and pollu-tion-free power generation, the increasing demand for continuous and peak power supply in the glob-al arena and the striving for reduced total cost of ownership are shifting the energy market towards renewable energy sources and gaseous fuels [1].

In recent years, stationary gas engines have achieved a significant share in the energy mix in many parts of the world since the ecological foot-print is much better than that of diesel engines and coal power stations [2].

As the share of gas engines will continue to rise in the global energy market and the emission legisla-tion gets tightened, engine manufacturers are progressively striving for a reduction of raw emis-sions and an increase of electrical efficiency. The developments made on the engine design com-prise higher peak combustion pressure [3], lean-burn combustion processes, advanced Miller valve timing and others [4].

The achievements made on the engine design have an aggravating effect on the valve train components. It has been observed by the authors that prevailing best practices for the design of valve spindle and seat ring may not be suitable to meet the future engine operation requirements [5]. For example, the requirements for contact pres-sure between valve spindle and seat ring to meet engine performance results are moving beyond existing design limits. In the latest developed test engines, severe wear occurs on the tribological system of valve spindle/seat ring, leading to re-duced lifetime or unexpected premature failure of the valve spindles with serious consequences for the engine.

The research on valve wear and its root causes requires a deep understanding of wear mecha-nisms. Valve wear is a multivariate, complex tribo-logical phenomenon influenced by thermal condi-tions, contact mechanics, chemical effects and material properties [6].

The design of valve spindle and seat ring as a part of the highly dynamic valve train system has to be considered from a holistic point of view to ensure a sound operation during the whole lifetime of the part. Therefore a novel approach for sustainable valve spindle and seat ring development has to be determined.

Valve wear as a tribological phenomenon has been subject to research in several studies in the past. Empirical studies were carried out regarding actual component testing of the tribological sys-tem valve spindle/seat ring, combining both the wear impact of valve closure and peak cylinder pressure [7], [8], [9], [10]. Other studies provide general numerical simulation approaches, written in various codes, to estimate wear of a metal-to-metal contact [11], [12], [13].

Lewis [14] and Lewis et al. [15] made extensive research with a valve component test rig and combined the test results with a classical calcula-tion method based on the Archard [16] model of wear to predict valve wear in the automotive in-dustry. The calculation model differentiates be-tween impact wear due to valve closure and slid-ing wear caused by peak combustion pressure. The wear coefficients for the sliding wear were based on results of standardized tests, e.g. per-formed by Rabinowicz [17] and the hardness of the materials. The work lacked the consideration of the complex load situation during the micro-sliding between valve spindle and seat ring as various tribological mechanisms superpose and / or dominate each other.

Past attempts to develop a precise and consistent valve wear model comprising all complex coher-ences of mechanical, chemical and thermal ef-fects as well as the influence of material proper-ties turned out to be inaccurate and incomplete for large-bore gas engines. None of the existing models return realistic results for state-of-the-art large bore gas engines and allow for separation of the valve closure and peak combustion pressure effects.

This research is the fourth phase of a multi-stage research project at Märkisches Werk GmbH. In the first phase [18], valve spindles from the same type of gas engines were studied to understand the properties-determining wear mechanisms. The second phase was followed up by the develop-ment, design and setup of a novel valve wear test rig [7]. In the third phase [19], individual test series of peak combustion pressure and valve closing velocity were carried out, in return giving evidence that the latter has a more profound influence on the tribological system valve spindle/seat ring in comparison to the former. The goal of the present research is to develop a numerical valve wear simulation tool which is capable of approximating the valve wear based on phase three of this re-search project.

The numerical basis on which valve wear is de-scribed is a modification of the wear model pro-posed by Archard. The experimental results of the test modes for valve closure and peak combustion pressure are used as input values for finite ele-ment (FE) wear simulations. The wear model is implemented to a numer ical ABAQUS simulation model. The amount of wear is estimated by a user sub-routine UMESHMOTION. This user sub-routine is the core of the valve wear simulation model since it allows for a change of the simula-tion mesh to achieve a geometrical displacement on the contacting faces caused by wear, following the modified Archard law of wear which is fed with the database generated by actual component testing.

Depending on the boundary conditions, the load (i.e., valve closing velocity, peak combustion pressure, temperature and surrounding environ-ment) and the material combination, the numerical model realistically simulat es the valve recession.

This work presents the valve wear model, the testing of the components, the numerical simula-tion model and the validation of the model.

2 VALVE WEAR MODEL

The framework for the valve wear model was based on Archard's model of contact wear be-tween metallic materials [16]. According to Ar-chard, the relative movement of two objects caus-es elastic as well as plastic deformation of the asperities at the contact interface depending on the normal load.

Equation (1) describes the wear volume ratio *Vw* as the product of a wear coefficient C_0, the contact pressure *p*, the contact area *A* and the relative sliding distance ṡ. This relation is a modification of the Archard wear model [16].

$$\dot{V}_W = C_0 p A \dot{s} \quad (1)$$

This relation expresses the wear volume for slid-ing contact. In contrast to the basic idea of Ar-chard to model the wear volume of idealistic slid-ing on flat surfaces, the wear model used in this investigation linearly depends on a wear coeffi-cient C_0 which comprises the influences of geome-try, material properties and wear mechanisms in one value.

Since the valve wear in large-bore gas engines is influenced by complex interdependencies, the wear coefficient C_0 has to be determined as a phenomenological value from experimental test series. Validated experimental tests allow for a determination of the wear coefficient C_0 under various load conditions, thus comprising all wear mechanisms and prevailing conditions which in-fluence the wear coefficient. This approach to model valve wear does not necessarily require a detailed understanding of all tribological mecha-nisms but relies on a rather phenomenological perspective.

3 VALVE WEAR EXPERIMENTALS

3.1 Valve wear tribometer

The target of the valve wear tribometer as shown in Figure 1 is to generate a valve and seat ring wear rate and to replicate wear mechanisms which are present at field parts operating in actual engines.

As simplified tribological tests like pin-on-disc tests generate often wear volumes far off from reality, the valve wear tribometer was designed as close as necessary to the real engine situation whilst allowing for full control of test parameters to return results as accurate as possible.

Figure 1. Valve wear tribometer

The valve wear tribometer is mounted on a test frame which is oversized to minimize any mechan-ical effects by elastic torsion. The setup of the tribometer allows for the assembly of original valves, seat ring and valve springs. Figure 2 shows a schematic over view of the test rig.

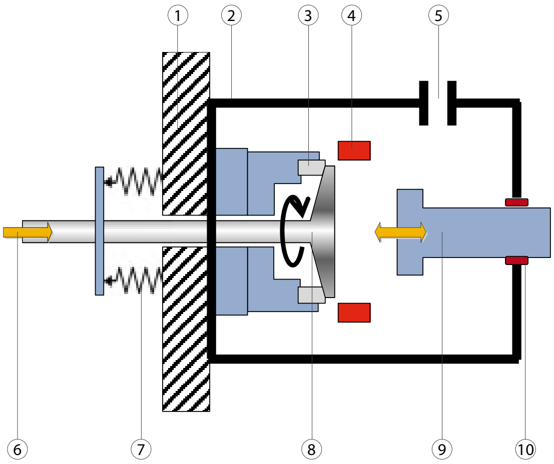

Figure 2. Schematic overview of the test rig [20]

Table 1. Description of Figure 2

1	Frame
2	Environmental chamber
3	Seat ring
4	Inductive heating
5	Gas inlet
6	Hydraulic cylinder
7	Retaining springs
8	Valve spindle
9	Hydraulic stamp
10	Shaft seal

A hydraulic cylinder is located at the valve tip end to apply a force simulating the valve opening and closing phase. Another hydraulic cylinder, placed at the valve face, simulates the peak combustion pressure mode. By this configuration, the tribo-meter can work in two different test modes with respect to both the impact wear induced by valve closure (test mode I) and the sliding wear induced by peak combustion pressure (test mode II). Both wear phenomena follow different mechanisms and can thus be analysed separatedly.

In order to simulate mechanical and kinematic load on the valve taking environmental variables into account, the test rig was also equipped with an environmental chamber. The chamber can be flooded with pure gases or gas mixes to simulate various actual engine conditions. The test compo-nent can be heated up inductively whilst the seat ring is cooled by a water jacket. The environmen-tal chamber provides a thermal insulation.

Valve rotation is ensured for both test modes valve closure and peak combustion pressure.

3.2 Test mode I

In test mode I, the tribometer simulates the valve wear caused by valve closure. The valve closing velocity can be adjusted up to 1.2 m/s at the initial contact. At test mode I the hydraulic actuator (6) (refer to Figure 2 and Table 1) moves the valve spindle (8), simulating the valve opening. The springs (7) are compressed whilst the hydraulic cylinder follows the actual cam shaft curve. The speed of relieving the force may be adjusted to simulate high or low valve closing velocities. During the experiments, the w ear on the valve seating face is measured after every 25 hours by a relief print. An original valve spring and valve rotator ensure the rotation of the valve.

3.3 Test mode II

Test mode II of the tribometer was designed to replicate the tribological effects on the valve spindle and seat rings at peak combustion pressure. The general assembly is similar to test mode I. The hydraulic stamp (9) is connected to the valve face and opens and closes the valve by about 1 mm with a velocity of 0.1 m/s, which is by experience of the authors low enough to avoid impact wear. After valve closure, the hydraulic stamp applies a force on the valve face equivalent to the peak combustion pressure. The design of the hydraulic stamp and the force which is to be applied to equal the peak combustion pressure was determined by finite element analyses. The position of the hydraulic cylinder (6) is arranged normal to the position of test mode I and offset to the valve spindle axis. During operation, the hydraulic cylinder actuates a mechanical subsystem to rotate the valve spindle, which cannot be performed by the original rotator due to the reduced valve lift.

3.4 Results and Validation

Any tribological transfer from a bench test to a red engine test is valid if the types of wear and the wear rates of the tested parts are in the same range as in case of the parts from the field application. The goal of the tribological validation is to prove the properties-determining wear mechanisms of the tribological system. The controlled variation of test parameters is the base of the tribological evaluation of the experimental results. A validation of the test rig as well as prior understanding of wear mechanisms in real applications is key for apposite evaluation and interpretation of results.

Lehmann [19] described the validation of the test rig in detail which is summarized in the following. The valve rotation was indirectly measured using force transducer, result ing in a negligibly small torque deviation of about ± 1 Nm. As a second mechanical criterion, the cooling system was checked. With regard to the test series, a 3-stage validation of the two major factors closing velocity (test mode I) and combustion pressure (test mode II) was performed. Velocities of 0.2, 0.6 and 1.0 m/s and pressures of 140, 180 and 220 bar attemperatures of 330, 380 and 430 °C were per-formed. Measured temperatures of valve spindle and seat ring varied in a range of 11 K for closing velocities and 5 K for combustion pressures. Fur-thermore, measured temperature differences from 198 up to 321 K between valve spindle and seat ring for all tests of closing velocities and combus-tion pressures are in accordance with literature [21], [22].

The types of wear as a first tribological parameter was also examined as part of the validation phase [19]. Different findings as result of comparative investigations with 0.6 m/s at room temperature and 330 °C demonstrate the capability of the test rig to replicate temperature-induced changes of microstructure and surface (see Figure 3). Wear scar widths of about 3 mm at room temperature in contrast to 6 mm at 330 °C were measured. Fur-thermore, strain gradients, broken hard phase structures as well as flakes, ridges and pits on the surface were observed at 330 °C, whereas similar effects could not be observed at room tempera-ture. The impact of temperature was also evident in test mode II at a combustion pressure of 180 bar (see Figure 4). In contrast to room tem-perature, flakes and a tribofilm characterize the wear appearance at 330 °C, whereas the wear scar widths at room temperature and 330 °C were of comparable size. The results obtained at high temperature from the component tests mimics the same types of wear and wear mechanisms as observed on the fired engine cell tests [18].

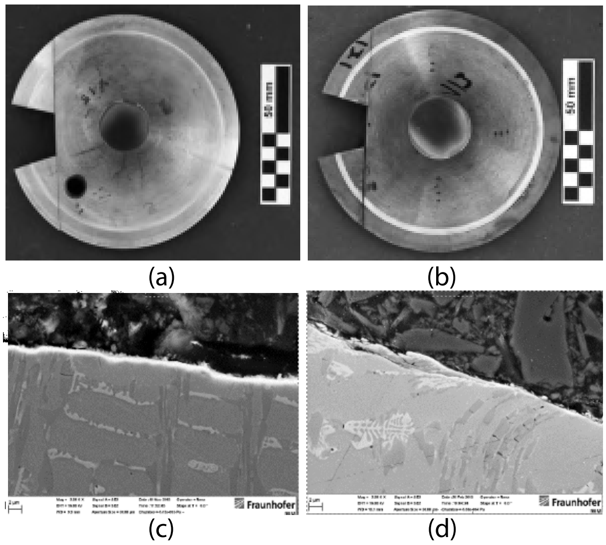

Figure 3. Comparison of the types of wear with 0.6 m/s, macrographs of valve heads at room temperature (a) and at 330 °C (b), SEM micro-graphs of cross-sections at room temperature (c) and at 330 °C (d)

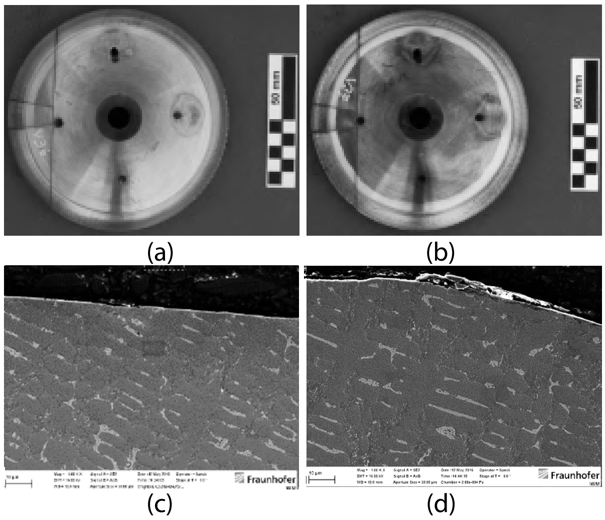

Figure 4. Comparison of the types of wear with 180 bar, macrographs of the valve head at room temperature (a) and at 330 °C (b), SEM micro-graphs of the cross-sections at room tempera-ture (c) and at 330 °C (d)

The second tribological parameter was the wear rate. For test mode I, a wear rate of 0.06 mm³/h was measured at room temperature, whereas the test at 330 °C accounts for 1.60 mm³/h at a com-mon valve closing velocity of 0.6 m/s (see Figure 3). As an example of the significance of the clos-ing velocity, a value of 3.33 mm³/h was measured at 450 °C and

1.2 m/s. Lehmann et al. [18] deter-mined values of the same magnitude from fired engine tests of 1.45 to 3.95 mm³/h. Thereby it can be stated that the test rig used to determine the wear coefficients is able to simulate the same types of wear and wear rates as known from fired engine tests.

4 WEAR SIMULATION

Wear simulation was performed to accurately calculate the progressive change of the worn surface geometry in the complex contact condition between valve spindle and seat ring. In order to integrate macroscopic wear into numerical simulations, a user subroutine UMESHMOTION was developed to ablate the material from the mating surfaces. A modified form of the Archard's wear model was applied in the subroutine as shown in equation (1). For x being the position and t the time, the volumetric wear rate Vw equals to

$$\dot{V}_W(\vec{x},t) = C_0 \int \dot{s}(x,t)\, p(x,t)\, dA \qquad (2)$$

In order to transform this equation (2) to an expression which can be used in a numeric environment, the volumetric wear rate can be expressed as the sum of the contact area A_n at node number &, multiplied with the ablation of the nodal position h_n. In this case, the direction of vector x is normal to contact area A, thus one-dimensional wear is described. The sum over contact area A is expressed by equation (3):

$$\sum_{n=1}^{N} \dot{h}_n A_n = C_0 \sum_{n=1}^{N} p_n \dot{s}_n A_n \qquad (3)$$

In order to incorporate this wear model in a finite element frame work and calculate the incremental volumetric wear, the rate of nodal ablation is ex-pressed by equation (4).

$$\frac{dh}{ds} = C_0\, p \qquad (4)$$

In equation (4), dh is the incremental change in height, and ds is the incremental nodal slip, thus the computation of wear is based on the local contact pressure p which is considered constant in a defined time increment. A detailed description of an integration of the finite element model and user subroutine can be found in [23], [24].

In order to simulate contact between valve spindle and seat ring, a model was created as shown in Figure 5, taking advantage of the axisymmetric geometry of the samples. The axisymmetric model was discretised with a finer mesh close to the contact region and a coarser mesh for the remaining geometry to ensure reduced computational time. 4-node bilinear stress and displacement elements (CAX4) were used to mesh the model. The element size 50×50 (µm²) on both surfaces in the contact zone was selected after numerous iterations with different element sizes. The validity of the mesh was checked by comparing results from a case study with various different mesh refinements in order to select a suitable mesh configuration.

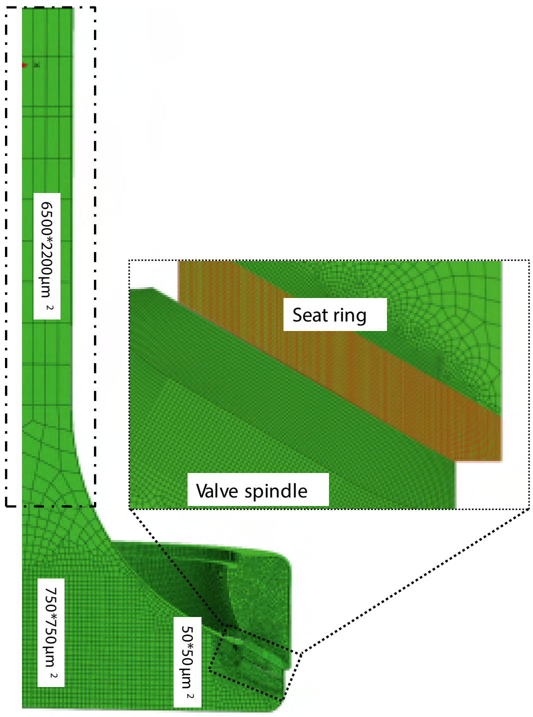

Figure 5. Axisymmetric model with mesh used for fnite element simulations

After discretisation, a quasi-static analysis procedure was carried out for accomplishing the following wear simulation using the implicit solver (i.e., ABAQUS/standard) in comb ination with a user subroutine UMESHMOTION. Figure 6 shows the axisymmetric model with boundary conditions (BC) and load as considered for the simulations. In both test modes, i.e. I and II, gas pressure was applied on the valve spindle face. In test mode I, the applied gas pressure equals the impact force and in case of test mode II, the applied gas pressure equals peak combustion pressure.

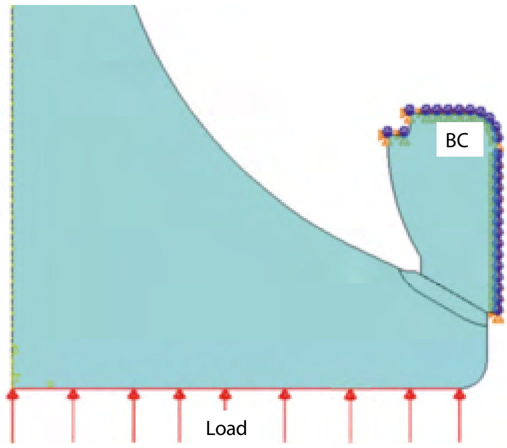

Figure 6. Load and boundary conditions (BC) on the axisymmetric model

The user subroutine UMESHMOTION is incorporated to the model in order to ablate the surfaces. A sequential technique was employed to ablate material initially from one surface followed by an-other. This is necessary due to the fact that the ABAQUS implicit FE-solver is not capable of cal-culating the ablation on both contacting bodies simultaneously.

5 VALIDATION

In order to prove the functionality of the developed subroutine several preliminary simulations were performed for short duration with and without material ablation. Initially simulation was performed without the wear subroutine to obtain the stresses in pristine condition. Figure 7 shows the compari-son between contact stresses on the surface of valve spindle under the same loading situation without and with wear on one surface.

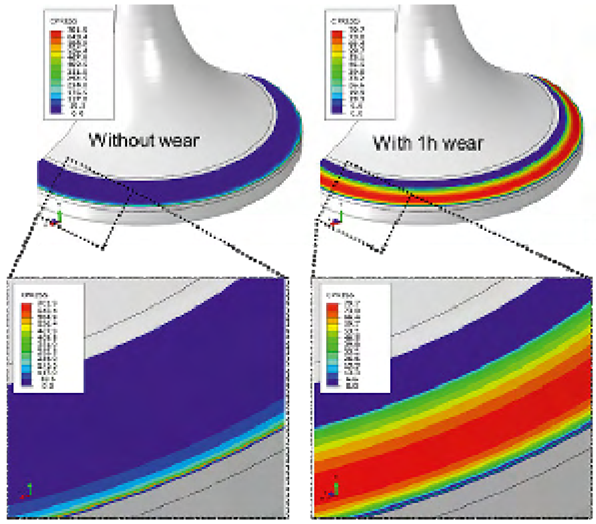

Figure 7. FE-generated contours showing the contact pressure without (left) and with (right) wear after 1 hour at F N=80 kN, T=330 °C

It is apparent from 1 hour (h) wear simulation that the contact area increases with decrease in contact pressure due to progressive wear on one surface. Figure 8 (a, b and c) shows the FE-generated contour of von Mises stresses and the graphs of contact stress distribution over the loading duration at the contac t interface between valve spindle and seat ring for unworn condition (a), with wear on valve spindle after 1 h (b) and with wear on valve spindle and seat ring after 1 h (c). It can be seen that in the unworn condition the peak stresses are confined to a small area and tend to evolve depending on the material ablation on both surfaces.

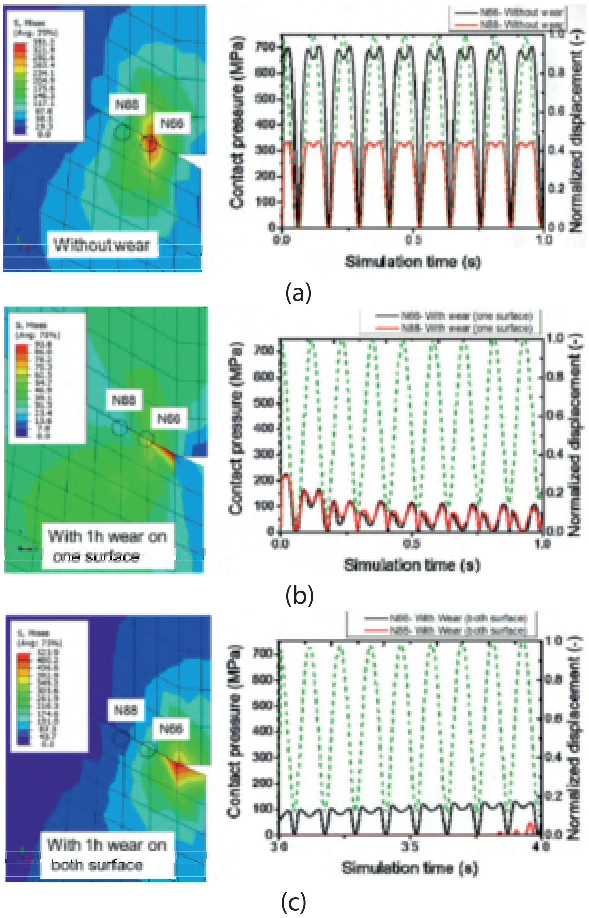

Figure 8. FE-simulation results showing von Mises stress (left) and graphs showing contact pressure (right) for (a) unworn geometry, (b) wear on one surface and (c) wear on both surfaces

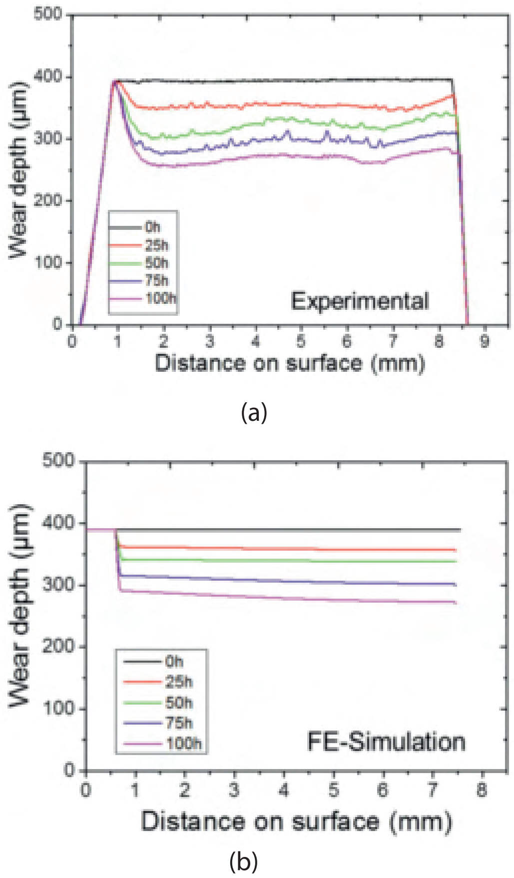

Figure 9. Wear depth profiles on valve spindle (Stellite™ 12 material) in test mode II (a) from experiment and (b) from FE simulation at F N=80 kN, T=380 °C

Sequential simulation (i.e., ablation on valve spindle surface followed by ablation on seat ring and vice-versa) was performed until the wear volumes as measured from experiments were reached. After ablating the experimentally measured wear volume, the experimental wear depth profiles were compared with the FE-simulated wear depth profiles for same working parameters. The simulations were performed for different material combinations as well as different modes (I and II). Figure 9 shows a comparison between wear depth profiles from experimental and FE simulation generated wear depths on a valve spindle hardfaced with Stellite™ 12 and a seat ring made of Pleuco 12MV material in test mode II configuration. From the results obtained it is evident that in spite of the superimposing wear mechanisms involved between valve spindle and seat ring contact, wear depth profiles could be simulated with high accuracy.

Moreover, the validation of the valve wear model was carried out simulating the wear on a combina-tion of a Tribaloy™ T800 hardfaced valve and a Tribaloy™ T400 hardfaced seat ring in both test modes I and II. Figure 10 (a and b) and Figure 11 (a and b) show a comparison between the wear depth profiles from experiment and FE simulation generated wear depths on valve spindle and seat ring for mode I and mode II respectively. It can be seen that the wear depth profiles simulated with FE simulation are in good agreement with experimentally measured wear profiles.

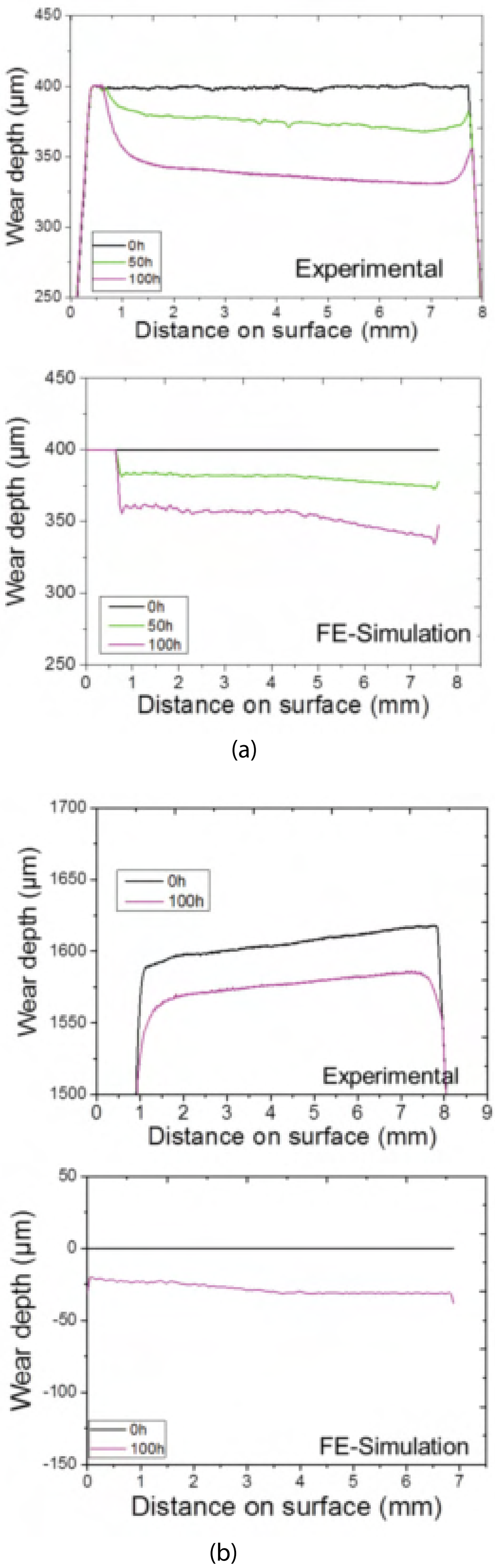

Figure 10. Wear depth profiles from experiment and FE simulation generated wear depths in test mode I on (a) valve spindle (Tribaloy™ T800 ma-terial) and (b) seat ring (Tribaloy™ T400 material) at F N=1 m/s, T=450 °C

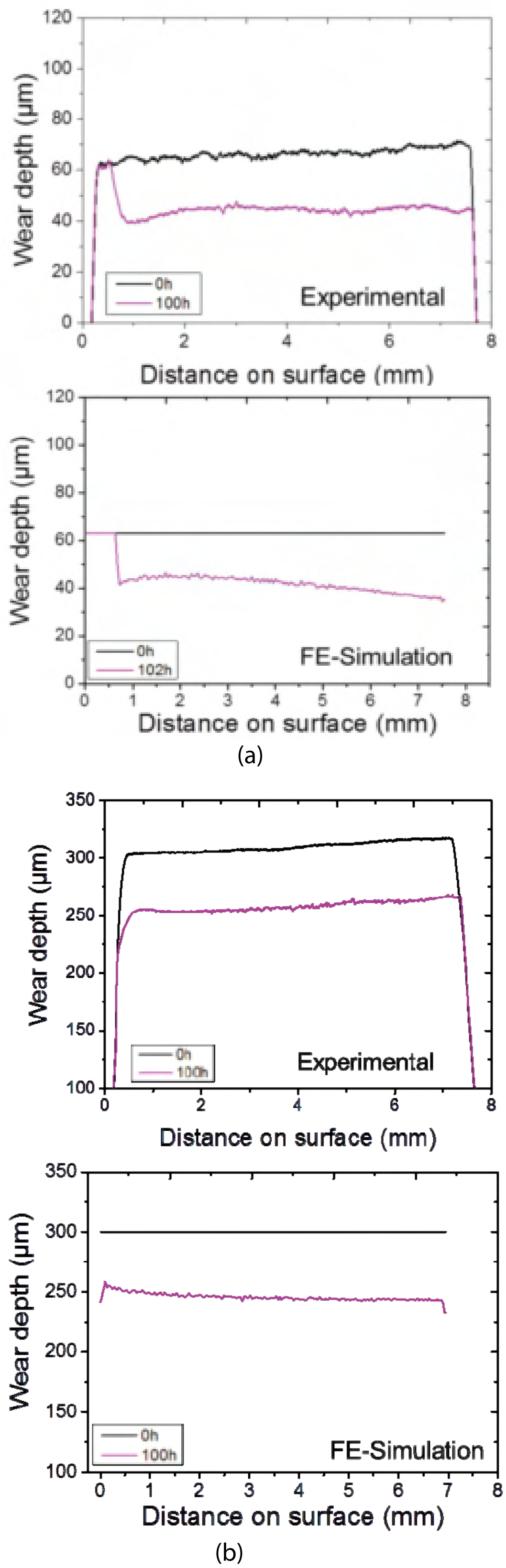

Figure 11. Wear depth pro files from experiment and FE simulation generated wear depths in test mode II on (a) valve spindle (Tribaloy™ T800 material) and (b) seat ring (Tribaloy™ T400 mate-rial) at F N=150 kN, T=450 °C

6 DISCUSSION

Due to increased demands of electrical efficiency and stringent requirements for reduced emissions, gas engines may require new design practices for the tribological system valve spindle/seat ring in the near future. A unique valve wear test rig and a novel approach of valve wear simulation shall contribute facing this challenge by providing new tools for reliable valve spindle and seat ring design.

The tribological test rig, which was developed in an earlier phase of this multi-stage research project, facilitated extensive tests of actual valve train components. The test rig was designed as a component test rig, aiming for a realistic test environment. For the first time, the validation of the test rig showed close consistency with the fired engine in terms of wear rate and types of wear. Even though the test rig is not fired, it was found that the wear rates and the types of wear generated on the test rig were in accordance with valve spindles from the field. The analyses of run test parts proved that the complex wear phenomena could be successfully replicated by the test rig.

The presented approach to describe wear in a systematic way is based on a modified Archard wear model. The mathematical description of the wear model was transformed into an incremental expression and incorporated into a finite element framework. The various tests carried out provided the according wear coefficients which are referred to in the finite element model. The finite element code of ABAQUS in conjunction with a user subroutine UMESHMOTION was used to compute the ablation on both the valve spindle and the seat ring surface.

The validation of the numerical model was done by comparing actual test rig results and numerical simulation results. It was found that the computed wear profiles are close to the actual measured wear profiles. The wear relief measured on parts from the test rig showed curvature profile on the inner and outer contact position, whereas the simulated wear graph had a rather sharp profile. In addition, some of the experimental wear profiles have some non-uniform waviness and variation in contrast to the computation results. Primarily, manufacturing and assembly tolerances and variations in the operational test parameters are not modelled in the finite element model, thus leading to deviations in the calculation results. Moreover, the wear coefficient is not measured in situ but rather as an overall value of a tested valve spindle/seat ring combination. The true wear coefficient might vary slightly along the contact zone. Generally, the FE simulated valve recession is very close to the measured valve and seat ring recession after distinct hours of operation. None-theless, the simulation results return a nearly simi-lar wear profile. For known tribological materials, it can be stated that the quality of results of the ex-perimental as well as FE simulation were close to worn valve spindles and seat rings from fired en-gine. Thus, it is possible to estimate the lifetime of the components valve spindle and seat ring. Cost-intensive performance tests of this cylinder head components using fired engine tests can be re-duced significantly.

Evidently, the presented valve wear model returns a realistic valve wear simulation for the tested materials. This approach is a first step to sustain-able valve spindle and seat ring design for future engines as the wear profiles and mechanisms can be predicted accurately. The impact of valve size, seating face geometry and material is respected in the model, thus an individual lifetime calculation for existing as well as future large bore engines with efficiency- or emission-optimized design can be carried out.

7 OUTLOOK

A unique test rig setup with the separation of two test modes, namely valve closing velocity and peak combustion pressure, and the development of a novel simulation model were successfully carried out and validated. The future phases of the multi-stage research proje ct will consist of further component testing with different materials, contact mechanics and test parameters to continue the development of a material database as part of a new design practice at Märkisches Werk GmbH. The simulation tool will be established to contrib-ute to the development of new highly loaded and environment-friendly engines, aiming for in-creased time between overhauls (TBO) by life-time-optimized design.

The testing and simulation validation were demonstrated for state of the art materials like Stellite™ 12 and Tribaloy™ alloys. Targeting for an increased lifetime of valve spindles and seat rings in large bore gas engines, the test rig in conjunction with the simulation tool will also be used to improve contact mechanics, particularly by geometrical changes and material selection. Further test series will be carried out using improved wear-resistant materials like MW-H5528-10 or MW-H5828-17 on seating faces.

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