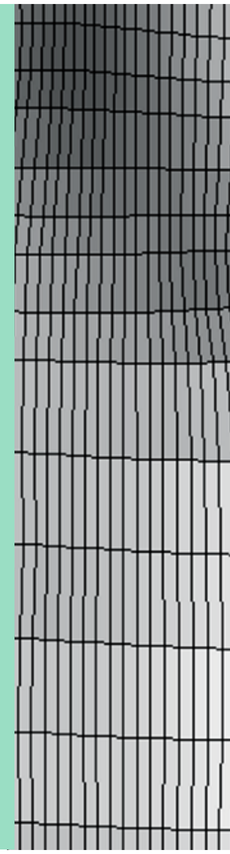

DEVELOPMENT TOOLS FOR BASE ENGINE FRICTION REDUCTION

Stricter limits for efficiency and emissions of combustion engines from legislation are increasing the focus on the reduction of pollutants and friction in the development process [1]. With ever shorter development cycles time efficient development tools gain importance for design, weak-point analysis and testing. Joining the competencies of the APL Group and the iST GmbH makes the therefor targeted base engine development possible through the combination of simulation and engine testing.

REDUCTION OF TEST BED AND FIELD TESTS

The highly loaded bearings in the crank train and the complex tribological system of the piston, piston ring and cylinder interface play an important role in the design of the base engine [2]. To achieve the maximal lifespan of the engine the wear rate of the tribo-surfaces should be less than a few nm/h. Effects in the material close to the surface, in connection with changes in the element mixture as well as the chemical and structural composition are essential [3]. In the conflict of objectives between friction power and oil emissions, the oil aging, which causes changes in the tribological and rheological fresh oil properties from incorporation of fuel, soot and water as well as oxidation processes and mechanical strain [4], is of particular interest. An optimal run-in of the engine can here contribute positively.

In particular by the piston group development opposing targets for reduction of friction and oil consumption leads to costly and time consuming engine tests. Whereas by hydrodynamic lubrication conditions the friction loss can be relatively accurate simulated, experimental friction coefficients are required by mixed friction. These are obtained by tribometer tests done at the relevant conditions. Besides the material and surface combinations, the lubricant and the thermal load, for instance the specific movement and speed of the tribosystem, which is determined by the crank train kinematic, are also to be considered when determining the experimental boundary conditions. In particular to consider are the dynamics of the ring pack and the resulting stroke-dependent contact mechanisms with varying friction. Beyond the validation of the friction power in the test highly accurate continuous measurements of the wear of specific tribo-systems with the radionuclide technique (RNT) are performed through radioactive activation of components.

The applied simulation tools for layout of the ring pack provide, besides friction

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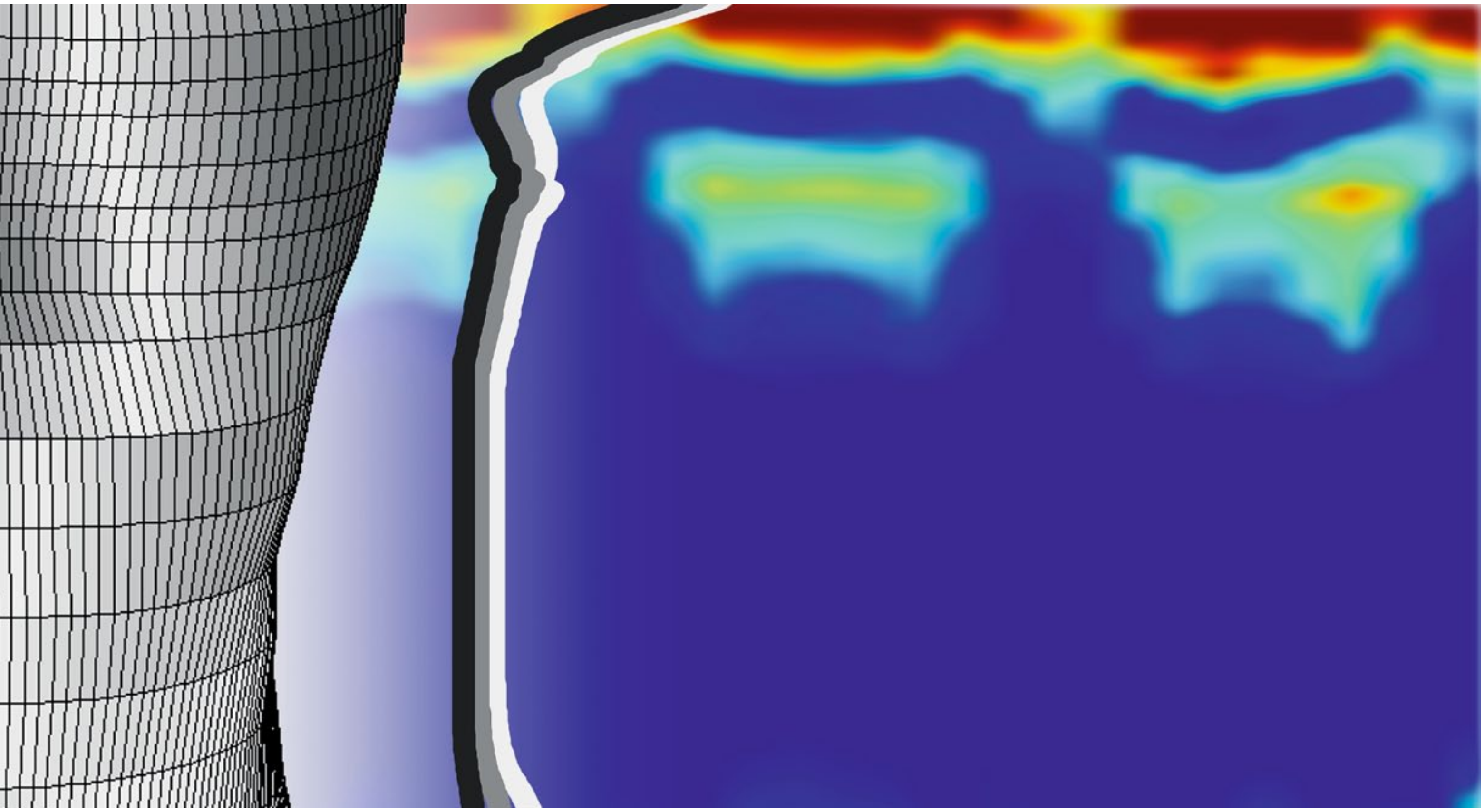
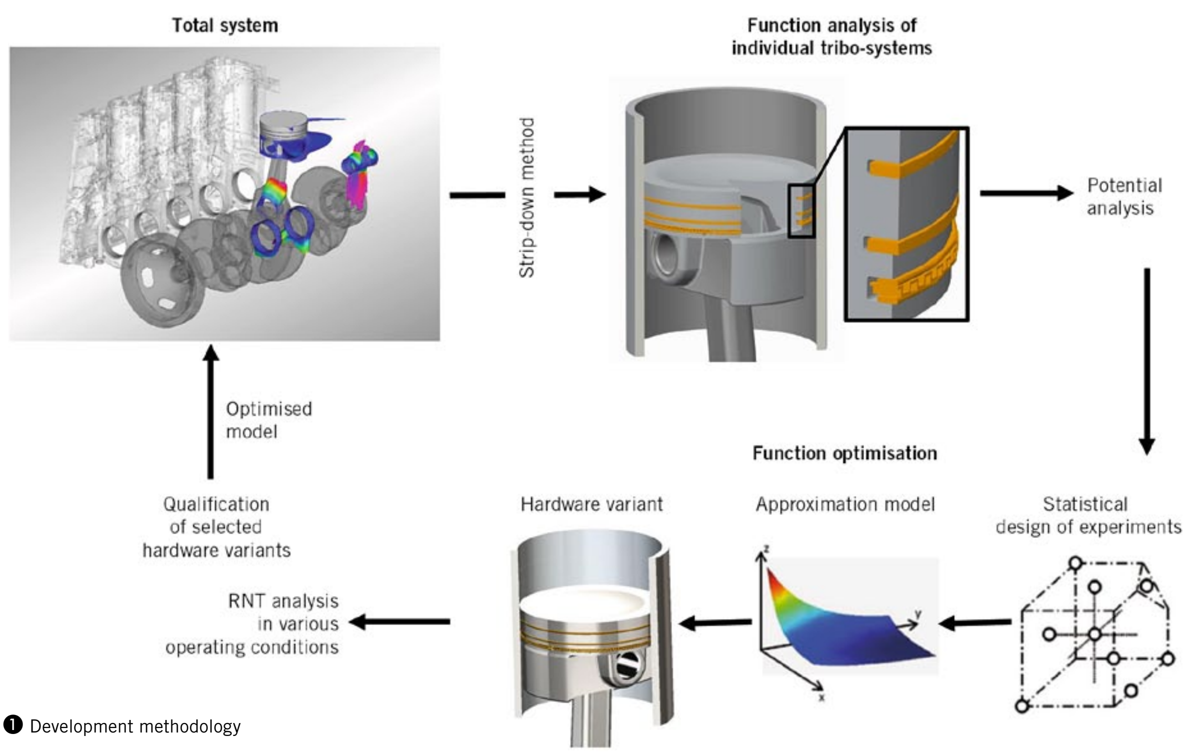


losses and sealing ability, information on oil volume (oil film thickness on the cylinder wall) and gas flow (blow-by and reverse blow-by) in the ring pack area. High-resolution simulation tools and online measurement techniques offer reduction in number of time and cost intensive test bed and field tests and provide an in-depth understanding of the functional interrelations as well as early findings of weak points and potential for optimisation.

DEVELOPMENT METHODOLOGY

The development methodology of the APL Group and iST is a combined experimental and simulative approach, ❶. Strip-down method motored meas-



❶ Development methodology

urements quantify the friction loss of the crank train, as well as of the auxiliary components. Simulation of the individual tribo-components of the crank train is validated by these measurements, where by the correlation is strongly dependent on the knowledge of the specific boundary conditions of the test.

SIMULATION

The simulation models allow prediction of contact and hydrodynamic portions of the friction by design and thermal changes of the system. The identified potential should be applied for fuel efficiency optimisation of new engine concepts. Building on a correlated calculation model the step towards engine boundary conditions is taken. The integration of the load spectrum over the entire engine map under variation of the design boundary conditions allows studying the effect on the friction losses. Thermal and operational boundary conditions are generated from fired engine tests.

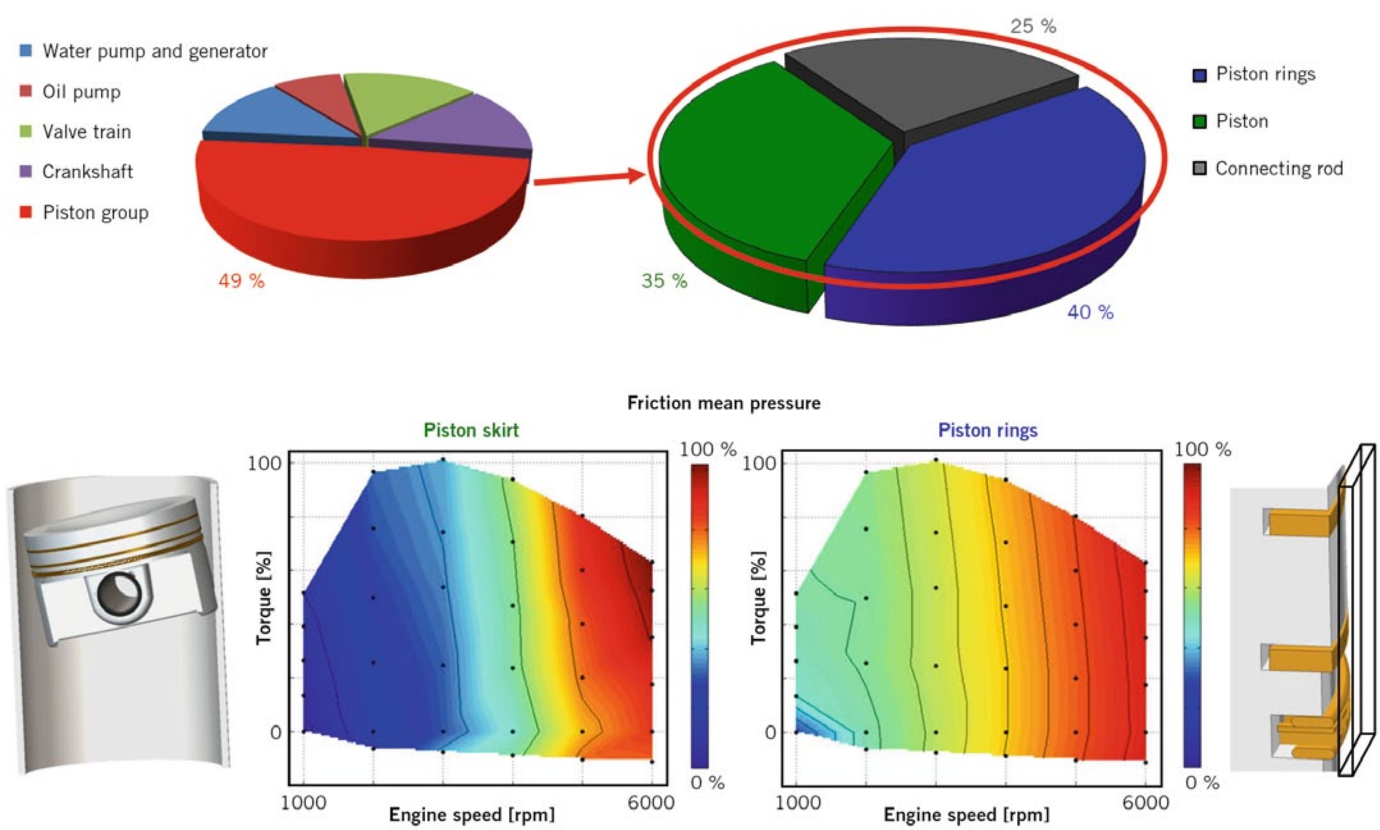
LOAD ANALYSIS

The load analysis over the engine load spectrum requires transient calculation algorithms where for the mechanical/physical modelling the important factors, besides the stiffness and mass of the components, their interaction at the different acting outer boundary conditions respectively the load spectrum are also to be considered. Augmenting the quality of the prediction from the simulation techniques for coupled tribo-systems requires consideration of the specific design of the parts based on finite element models, their material properties as well as the mechanisms for load transmission due to the highly non-linear reaction forces from the oil film. The therefore required physical models describe the elastohydrodynamic oil film reaction forces including the occurring asperity contacts based on an extended hydrodynamic lubrication theory for rough surfaces. Besides the power-laws for lubricants geometrical deviations of the functional surfaces from load, thermal and assembly effects as well as their micro structural properties are to be considered [5].

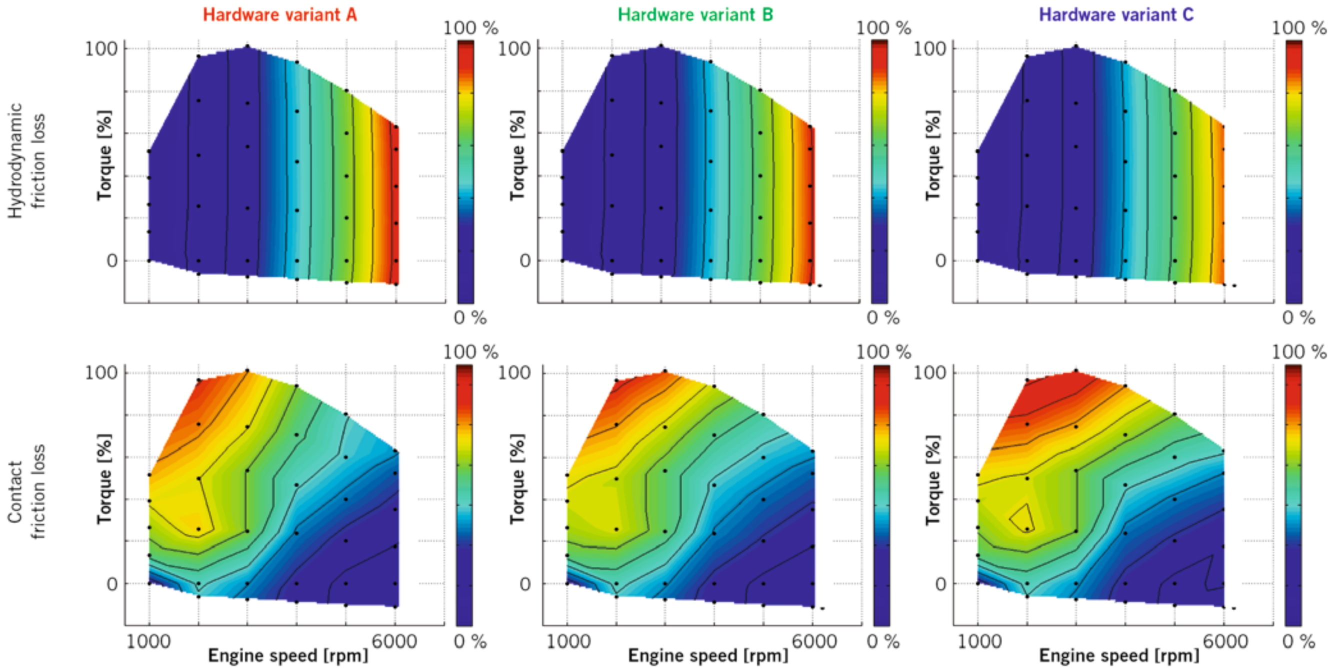
The main bearing and the connecting rod bearing simulation, the friction calculation for the piston-cylinder interface as well as the piston ring dynamics are done with the software packages First [6] and Kori3D [7]. Both were developed further for the development process and implemented in pre- and post-processing Matlab routines.

FRICTION DISTRIBUTION

In ❷ the friction distribution over different components at one load point is pictured and it is clear that a considerable contribution comes from the crank-train. The distribution changes depending on the operating conditions and is shown in an engine map for the piston group. Various measures for reducing the coefficient of friction of the piston group are, besides lowering the tangential force and the height of the top ring, the optimisation of geometry as well as the application of different honing processes and coating of the friction sur-



❷ Friction loss by various components from simulation and measurements

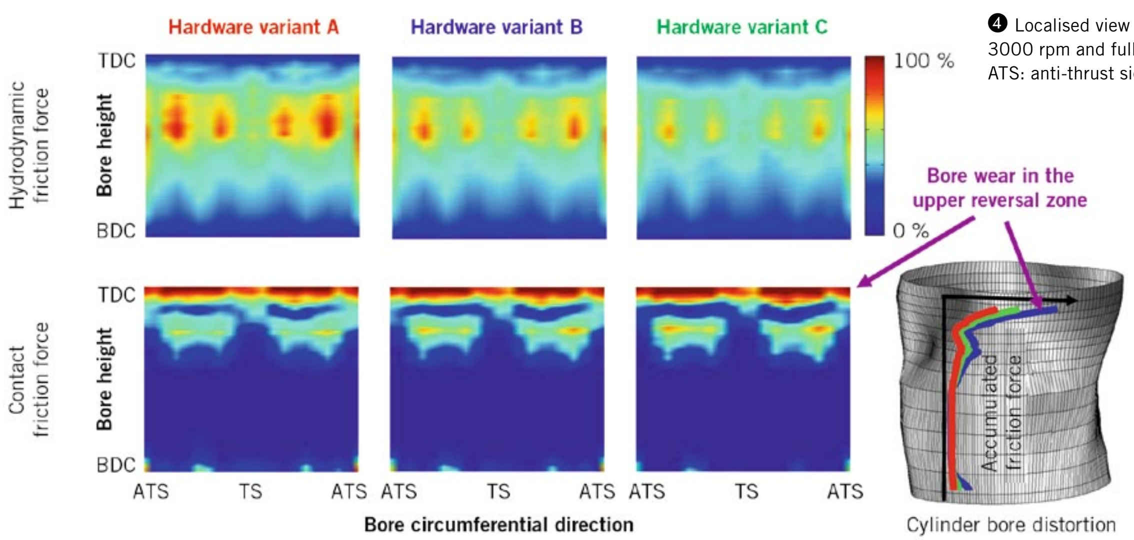


❸ Mapped friction loss behaviour of various hardware variants

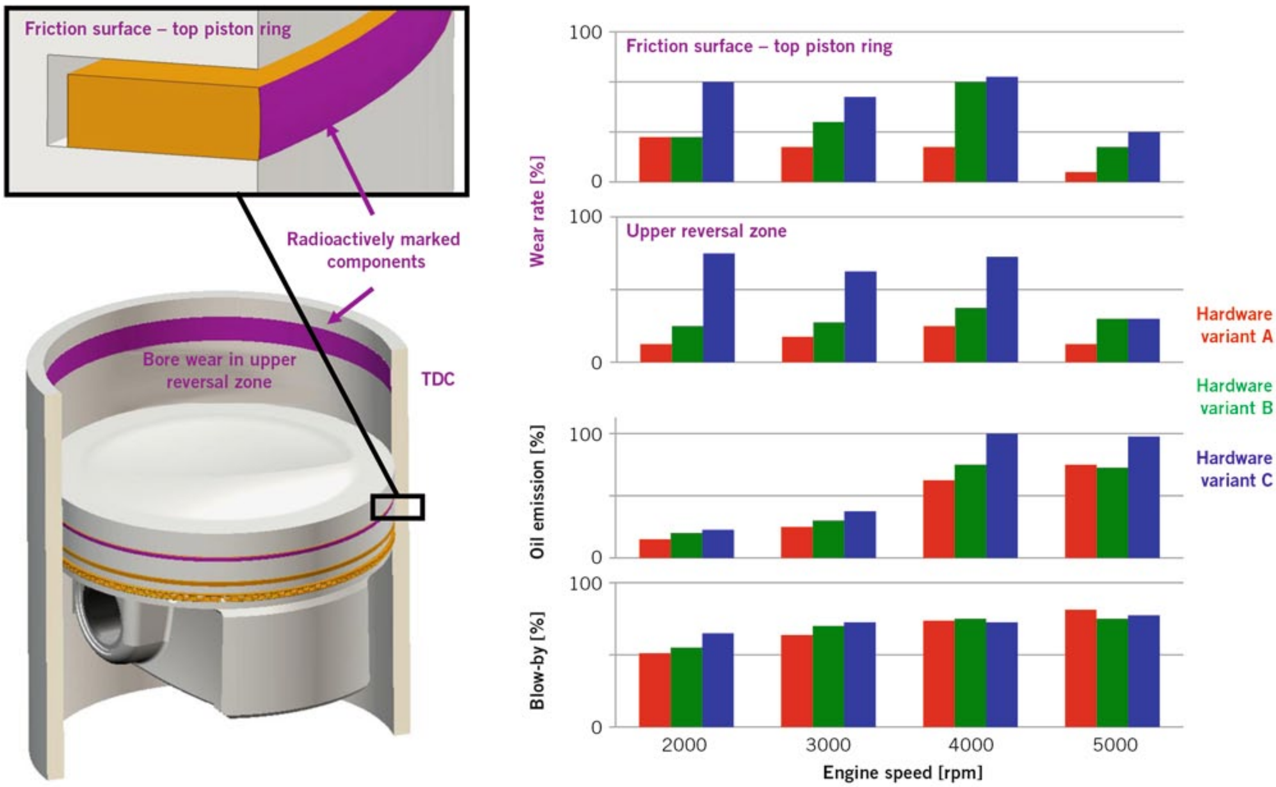
faces. By the layout of the system the behaviour of the total system with the influence of operating conditions and the cylinder distortion should be considered.

A combination of various measures leads to a change in the friction loss and is shown in ❸ for different hardware variants of the piston group. Due to the changes a considerable reduction of the hydrodynamic friction loss is achieved at high engine speeds. The contact friction is only higher by full load so that in total a change to the better is achieved.

Especially the increase in contact friction, in the area with full load, prompt a more detailed analysis of the simulation results. In ❹ is shown the calculated share of the friction forces for the hardware variants of the top ring at 3000 rpm and full load. The local distribution on the cylinder wall over the height of the cylinder for a complete working cycle is shown. The friction forces differ between the variants over the cylinder surface mainly due to the cylinder distortion of the higher Fourier-orders. Thereby the load increases in the areas of less radial expansion. In the area around TDC after ignition the low relative speed between the friction surfaces lead to high contact forces. Especially for the hardware variant C is due to the increased friction and its local concentration higher bore wear in the upper reversal zone to be expected.



❹ Localised view of friction behaviour at 3000 rpm and full load (TS: thrust side, ATS: anti-thrust side)



❺ Wear rate, oil emission and blow-by at full load for various hardware variants

WEAR

Besides design parameters, lubrication and lubricant, material, macro and micro geometry, the manufacture, or finishing is becoming increasingly important. Especially friction and wear phenomena by the piston group are subject to influences from the surface as well as the volume close to the surface of the piston, the piston rings and the bore. Due to the required durability the wear rates have to be very low. An extremely high resolution measurement technique with RNT is required to perform online measurements of these low wear rates. This technique allows the parallel measurements of two components due to the differentiation between different areas in the gamma energy spectrum of the individual nuclides used. In the preparation for the measurements the friction surfaces of the top piston rings and the bore in the upper reversal zone are differently marked radioactively.

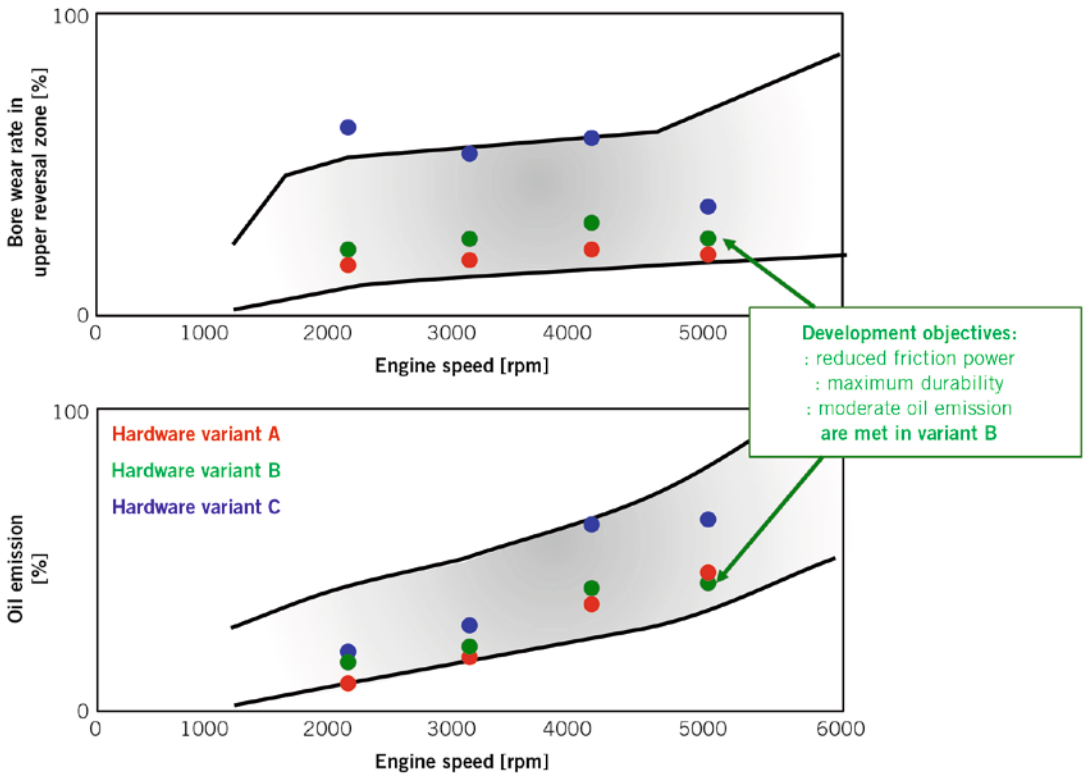
OIL EMISSION

❺ shows the influence of the hardware variation on the, with mass spectrometry measured, oil emissions and the blow-by behaviour by full load at various engine speeds. Furthermore the wear rates on the ring surfaces and the bore in the upper reversal zone are measured with the RNT. Especially by variant C the increased wear rates of the top ring and in the upper reversal zone confirms the distinctive contact pressure distribution from the simulation. By variants B and C at comparable blow-by values differently distributed increases in oil emissions at higher engine speeds are noted.

The achieved results with the variants are placed in the respective APL Group scatter bands for oil emission and wear rates, ❻. As the variant C shows border line wear behaviour the variant B combines reduced friction losses at maximum lifetime of the tribo-system under the boundary conditions of moderate oil emission and blow-by values. This compromise meets the set development objectives.

CONCLUSIONS

The reduction of friction is an important factor for the effort to reduce CO_2 emissions. Therefore it is necessary to identify the potential and to implement a set of targeted individual measures over the full engine map. With validated simulation models every tribo-component of the crank train can be simulated for friction optimisation and the number of component variants to be tested can be reduced. Under consideration of opposing targets, e.g. blow-by and oil emissions around the piston group and the durability of the engine the measures are developed and validated in engine tests with modern measurement techniques. The benchmark analysis allows by the usage of scatter bands to qualify the achieved results against the competition.



❻ Evaluation of results by scatter bands

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