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## Joint development of the bearing system for AVL's new high-speed engine platform

Engine Component Developments - Components

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## ABSTRACT

As human-driven climate change is a fact, drivetrain developments have evolved. Car and truck applications are shifting from ICEs to BEV and FCEVs, although the overall benefit (cradle to grave approach) is heavily discussed. The situation is different for the so-called large engine segment (high speed, medium and low speed) as the power density of batteries and the upscaling of fuel cell technology are still obstacles.

AVL's development of a new high-speed engine platform (HSLE) focusing on maximum efficiency and robustness for standard (diesel and natural gas) as well as upcoming CO<sub>2</sub> neutral renewable fuels (e-fuels, H<sub>2</sub>...) will prove the sustainability of the ICE concept.

To meet the major development target of 35bar BMEP, in combination with a robust design several development stages are implemented specifically on the power unit.

Bearing systems (BEB, SEB) capable of high peak firing pressures up to 340bar need specific design and simulation efforts to ensure maximum performance and robustness.

In addition to the technical requirements, future bearing systems must apply to upcoming regulations concerning hazardous materials.

The paper therefore deals with the development of the bearing systems for the described HSLE engine power unit starting with the design and simulation, and the verification within a SCE demonstrator. Specific attention has been placed on the bearing system (in a joint approach between AVL & Miba), focusing on the hydrodynamic layout, the influence of the system oil supply, the appropriate material selection and measurement verification, as the BEB and SEB are a key success factor combining maximum performance with necessary robustness.

## 1 INTRODUCTION

As a result of human-driven climate change, drivetrain developments continue to evolve to reduce consumption and emissions. Car and truck applications are shifting from ICEs to BEV and FCEVs, although the overall benefit (cradle to grave/ well to wheel approach) is heavily discussed. The situation is different for the so-called large engine segment (high speed, medium and low speed) as the power density of batteries and the upscaling of fuel cell technology contain significant obstacles.

AVL's development of a new high-speed engine platform (HSLE) focusing on maximum efficiency and robustness for standard (diesel and natural gas) as well as upcoming CO<sub>2</sub> neutral renewable fuels (e-fuels, H<sub>2</sub>...) will prove the sustainability of the ICE concept.

To meet the major development target of 35bar BMEP, in combination with a robust design, several development stages are implemented specifically on the power unit.

Bearing systems (Big End Bearing, Small End Bushing) capable of high peak firing pressures up to 330bar need specific design and simulation efforts to ensure maximum performance and robustness.

In addition to the technical requirements, future bearing systems must apply to upcoming regulations concerning hazardous materials.

This paper therefore deals with the development of the bearing systems for the described HSLE engine power unit starting with the design and simulation, and the verification within a single cylinder (SCE) demonstrator. Specific attention has been placed on the bearing system (in a joint approach between AVL & Miba), focusing on the hydrodynamic layout, the influence of the system oil supply, the appropriate material selection and measurement verification, as the BEB and SEB are a key success factor combining maximum performance with necessary robustness.

## 2 AVLS HSLE2025+ ENGINE PLATFORM

### 2.1 Development targets

To cope with the demand for future emission and fuel consumption targets as well as highest power density the New HSLE2025+ (high speed large engine) was designed for a BMEP of 35bar in a range from 1200 to above 1800rpm as well as in cylinder pressures up to 330bar. With focus on later serial

production capability the layout of the power unit was focused on realistic boundary conditions in view of a potential multi cylinder engine (MCE), producibility (design for forging and casting), weight, packaging and lifetime resulting in challenging thermal and mechanical load.

### 2.2 Approach

For maximum flexibility in view of development the design considered different combustion system variations as there are direct injection Diesel, active and passive gas pre-chamber, direct injection H<sub>2</sub>, etc. [5] The cooling and lubrication system consider flexibility in view of conditioning for various sub-supplies. Based on this approach AVL designed, procured, and assembled the HSLE 2025+ SCE.

### 2.3 Development partners and Funding

The research engine testing was performed as part of the COMET competence center program and was supported by the federal government and the provinces of Styria, Tyrol and Vienna. In addition, industry partners for the main engine components MIBA (plain bearings), KS (pistons) and MWH (valve train components) have participated and supported. Further partners providing support were TENNECO (piston rings), GIENANTH (cast cylinder head and block), and HYTORC (cylinder head bolting system).

## 3 MIBA'S LEAD FREE HS ENGINE BEARING PORTFOLIO

Based on the regulations for Pass car applications in the late 1990s, Miba already started in the early 2000s with the development of lead-free bearing solutions for large bore engines. In line with the SoP (Start of production) of the Daimler HDEP Platform with the OM 470-473 series Miba supplied the first lead free bearing solution for Truck applications. To achieve the performance goals in combination with sufficient robustness, the so-called Miba 69 was introduced, consisting on a lead-free Cu based lining (on a standard steel shell) with an AlSn20 Sputter coating a polymer running in layer. This combination has excellent performance characteristics concerning load capabilities and bearing life but is sensitive concerning adaptability and dirt ingress. Nevertheless, special care had to be taken on the system layout, production quality and assembly cleanliness. To improve the overall robustness the Synthec® running in layer has been introduced. Miba produced and supplied the OM47x series for more than 10 years. Millions of bearings proved the viability of a lead-free high-performance bearing solution.

#### **a. History of bearings materials (load limitations)**

Besides the serial release of a lead-free plain bearings for heavy duty truck applications all the other large bore engines with a bore diameter > 140mm were and are still based on leaded lining materials and partly lead based coatings. In addition, Al-bimetals are used for medium loaded applications and in the so called Medium and low speed engine segment.

Starting with the classic Steel-lead bronze – high leaded electroplated overlays to lead free plated overlays and Polymer coatings (as running layers) to Sputter and Sputter Polymer coated overlays Miba covers all the application needs using Diesel, Marine Diesel, HFO fuels and Gas.

#### **b. Next generation fuels & implications to lubrication & bearing system**

Ongoing developments for efficiency leading to increase of PFP (peak firing pressure) and the need for avoidance of deposit formation within the combustion chamber, forced a significant change of additive formulation especially for high end gas engine application.

Consequently, oil aging accelerated significantly impacting the long-term stability of the bearing system. Especially lead is washed out by acidic oils.

For reaching the required TbO targets (Time between Overhauls) a change of bearing materials has been a must for the described gas engine applications. As a lead-free bearing solution was available and in serial production already for many years, Miba 69 has been introduced. Performance wise this transition gave the opportunity to further increase TbOs, on the other hand short term failures after assembly and especially after service increased, as the overall robustness against early life and externally induced failures is lower compared to the well-known leaded compounds.

For the upcoming changes towards zero impact fuels on climate change as e-Methanol, NH<sub>3</sub> and H<sub>2</sub> impacts on the lubricant have to be expected as well. In addition, legislations prohibiting hazardous materials (as lead) are in negotiation and will get effective within the next 5 years.

#### **c. Next generation bearing portfolio**

Therefore, Miba is developing a consistent (lead-free) bearing portfolio trying to cover all different aspects as performance, robustness and design.

For the coating (= running layer) most of the layers (AlSn SnCuSb Sputter, Polymer (Synthec®)

already fulfill the upcoming legal requirements. With the serial release of the SnSbCu coating a robust lead-free electroplated layer is available as well, combining excellent emergency running capabilities with adequate long-term performance covering medium bearing loads [3].

As mentioned earlier, nearly all big bore engines (>140mm bore) using Tri-metals, run on lead bronze lining material. The actual lead-free lining (Gen I) had some deficits concerning robustness as lead is an excellent tribological active material. Therefore, the target for the Generation II was the improvement of emergency running capabilities and dirt resistance, keeping the pure performance (load capability) on the same level.

The final solution combining all the aspects is a CuSbZn Matrix with excellent fatigue behavior replenished with Sulfur particles to substantially improve the tribological behavior. Cross sections of the Gen I and Gen II materials are depicted in Figures 1 and 2. The Sulfur particles are clearly visible in Figure 2. Besides also the machining properties could be enhanced, resulting in scrap rate reduction, improved surface quality and longer tool life.

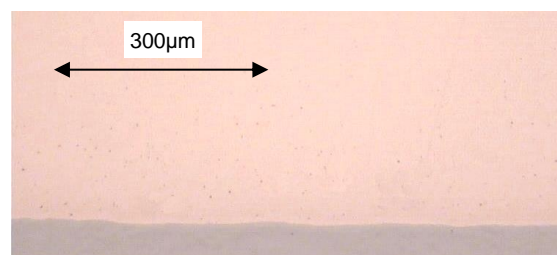


Figure 1. Cross section of CuSnZn Lead free bronze Bimetal (Gen I)

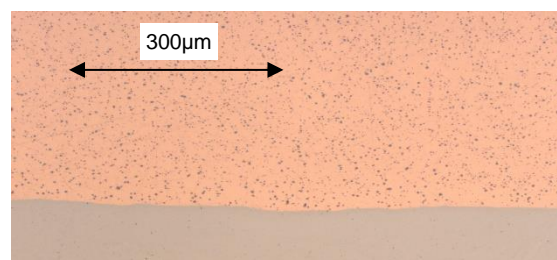


Figure 2. Cross section of CuSnZnS Lead free bronze Bimetal (Gen II)

For covering all bearing positions, the prescribed prefab material will be available in a strip casted as well as in a spin casted version. In combination with the well-established coating options (Sputter, E-plating and Polymer) for half shells and as a Bi-metal and E-plated version for the bushings, all bearing locations within an engine can be covered,

taking the performance as well as robustness needs into consideration.

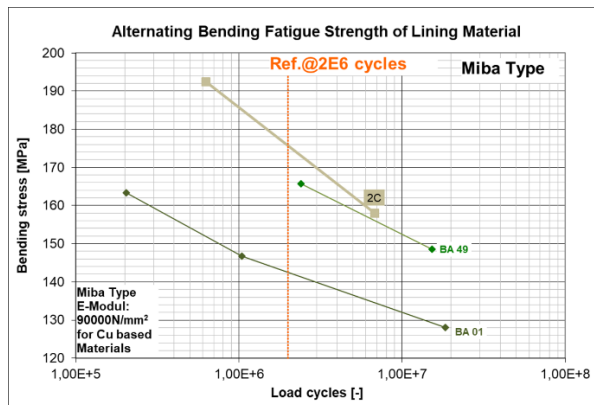


Figure 3. Alternate Bending test results of Steel bronze materials – Miba 01 lead bronze, Miba 49 lead free bronze Gen I, Miba 2C lead free bronze Gen II

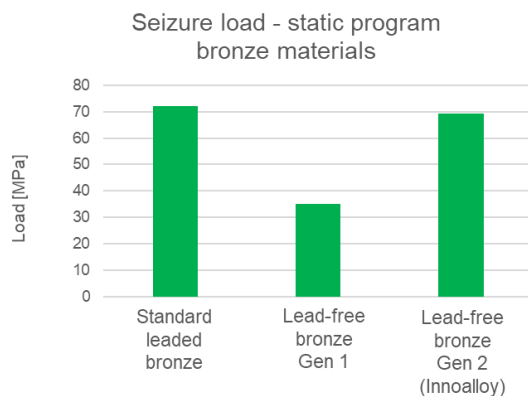


Figure 4: Test rig seizure load result of Miba 01 lead bronze, Miba 49 lead free bronze Gen I, Miba 2C lead free bronze Gen II

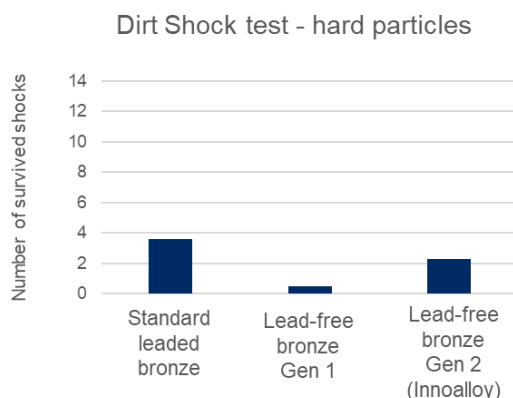


Figure 5: Dirt shock rig testing result of Miba 01 lead bronze, Miba 49 lead free bronze Gen I, Miba 2C lead free bronze Gen II

For prequalification of the base material specific tests (seizure load and dirt shock – see Figures 4 and 5) have been performed on the Bi-metals, in addition to the Miba internal qualification standard [2]. Figure 4 shows significantly improved seizure load level of the Gen II material in contrast to Gen I, comparable to the lead-based lining material. Concerning the number of survived dirt shocks depicted on Figure 5 a substantial increase to ~2 dirt injections could be achieved. In addition, the pure fatigue limit of the new Gen II alloy (2C) is slightly higher than the previously used material (49) and significantly higher than the lead-based lining (01), visible in the Wöhler chart on Figure 3.

To prove and verify the capabilities of this new lead-free portfolio Miba provided all the relevant bearing types for the connection rod (BEB and SEB) for the target AVL HSLE platform. Concerning the SEB a spin casted Bimetal version of the CuSnZnS alloy has been used. For the BEB 3 different types have been provided and tested. 2 Sputter versions AlSn20 / Synthec® (Miba 6G), SnCuSb (Miba 3H) and a SnSbCu electroplated version (Miba 4B) all based on a strip casted lead-free bronze (Miba 2C). Details of the bearing validation are described in Chapter 6.

## 4 DEVELOPMENT OF POWER UNIT & BEARING SYSTEM

### 4.1 Design process

In a single loop design and analysis front loading development approach AVL has used its internal benchmarking, design and analysis capabilities to implement a multi-cylinder capable single cylinder demonstrator unit. To reduce time and cost for validation and testing AVL followed the frontloading approach and reached a functional unit within shortest time demonstrating the full target achievement without mechanical failures.

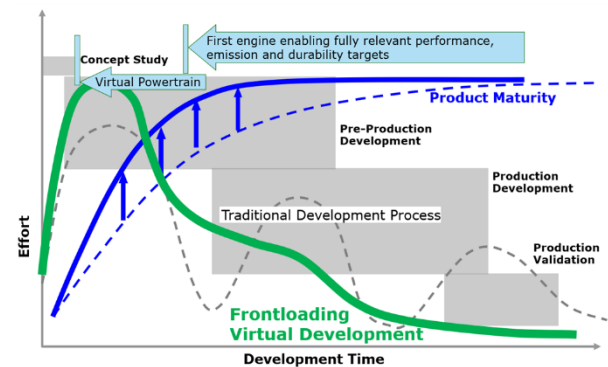


Figure 6. Frontloading and virtual development versus traditional development



In order to further push design and analysis capabilities ahead, the telemetric measurements and additional sensor across the engine have been used to confirm the predicted / frontloaded data.

For the bearing system in detail the temperatures on bearing shell back have been monitored live via a telemetric system and compared to the predicted bearing temperatures based on simulation.

## 4.2 Simulation Process

The virtual release and development of the components for the challenging next generation needs careful application of the CAE toolchain (available at AVL) in an early development stage as shown in Figure 6. Most challenging is the wide range of target application in combination with the target of 35bar BMEP resulting in highest demands for each single component in terms of mechanical and thermal loading. The focus is on the piston cylinder unit.

### a. Conrod bearings

The challenge of 330bar firing pressure in a wide range on the speed profile is to balance overall dimensions between reduced structural stiffness and sufficient remaining strength.

The small end bushing is implemented without forced lubrication and hence needs withstand high load under poor lubrication. Reaching a unit load of 123MPa demands an excellent load distribution over width and matching between the piston pin stiffness, small end form shape and small end structural support. To ensure functionality for the system from the beginning, a form shape defined based on EHD simulation (Figure 7) maximising the load distribution area in the bush center for load carrying capability. A feature including a smooth transition to a strong relief on the edges was also implement.

Similarly, the big end bearing needs be defined with an accurate micro-geometry to meet the surrounding structure's demands. Avoiding high edge contact and ensuring a proper circumferential and axial load distribution. The results show that sufficient softness at the thrust faces towards the webs is required to achieve safe results on the big end bearing and avoid the demand for high run-in layers on the bearing running face.

Such a simulation using AVL Excite Power unit MBD software [3] requires detailed modelling of the piston, piston pin and conrod (shown in Figure 7) as flexible bodies to allow for correct interaction between the structural components. As side effect of the dynamics, simulation of the small end the

shape and dimensions of piston pin and piston bosses is confirmed as well.

During the dynamic simulation of the bearing / bushing system the limiting curve for cylinder pressure versus speed had been developed to establish the mechanical boundaries for combustion development.

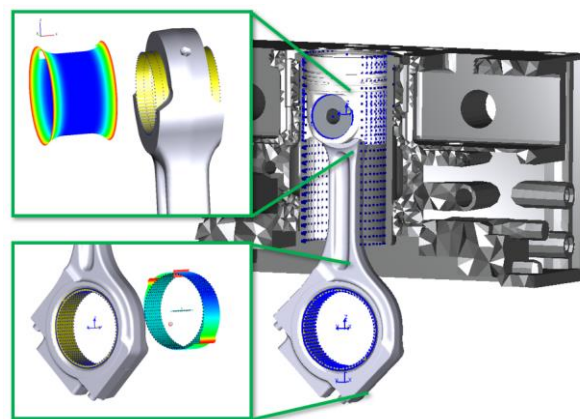


Figure 7. 3D representation of the virtual twin for the bearing system

### b. Main bearings

The main bearings for the single cylinder have been defined to ensure safe and long-lasting operation without demands and have been slightly over-dimensioned in diameter. Nevertheless, the multi-cylinder bearings have been virtually confirmed up to V20 in 3D EHD simulation to ensure the engine can meet the overall targets in terms of balance of crankshaft length, bearing width versus web width and cylinder spacing for the 35bar BMEP target.

## 4.3 Conrod: Mechanical layout and bearing assembly test

Two of the main tasks for on the powertrain design are the layout and design of the Conrod big end bearing (BEB) and small end bushing (SEB). For the SEB a layout with a microgeometry defined by MBD / EHD simulation for achievement of harmonic pressure distribution has been chosen. Besides that, special care has been taken designing the oil pockets and grooves to achieve an adequate oil supply by splash oil collection without an oil channel through the conrod shaft for pressurized oil supply.

To ensure a precise ID shape the final small end machining including a form bore has been done after bushing assembly.

Concerning the BEB layout a standard design has with an overall half shell wall thickness of ~5mm

has been selected in combination with a crush of  $\sim 0.15\text{mm}$  (per shell) to guarantee an adequate press fit. For final definition of the wall thickness shape, an assembly test has been performed on the first conrod available. As shown in Figure 8 a slight ovality has been measured, therefore a wall thickness “correction” of  $0.03\text{mm}$  has been specified on the final drawing.

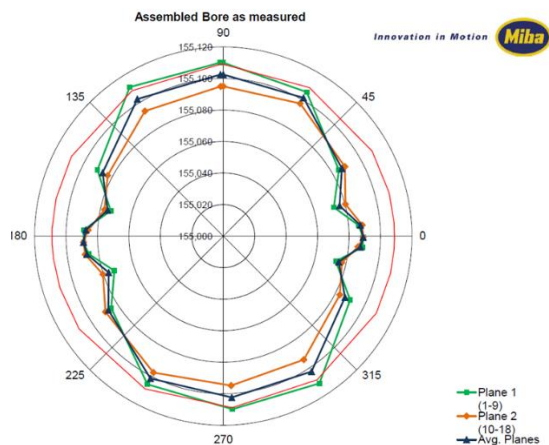


Figure 8. Assembly test result using bearings with constant wall thickness

## 5 SCE SET UP AND INSTALLATION

### 5.1 Quality check of parts with focus on bearing system

To reduce the risk of severe engine failures, in advance of engine assembly and in addition to conducted simulation tasks, the connecting rods have been validated by fatigue testing. The quality of all components was proven and documented with a 100%-dimensional measurement and material inspection for relevant components such as cylinder head, block, bolts, conrods, etc.

### 5.2 Power unit assembly & engine built up

During the assembly, in addition to the part quality checks, geometrical measurements on relevant assemblies influenced by the assembly loads as the bearing systems were performed to prove the influence in view of deformation. This was to avoid any later engine issues and to prepare a basis for later wear assessment for the relevant tribological pairings e.g., the valve-to-valve seat ring interface, by documenting the valve recess in assembled condition.

### 5.3 Installation of Conrod BEB incl. monitoring system

For an adequate monitoring of the powertrain especially of the BEB a newly developed Telemetric system has been used. In contrast to state-of-the-art systems which are used for

development engines, with limited operation time due to limited electric capacity of the battery. The applied system uses an induction system for power supply. The whole system consists of a telemetric system including an induction system and the temperature sensors mounted on the conrod (Figure 10) and a permanent magnet mounted on the crankshaft (CAD mock up see Figure 9). The relative motion between the induction system and the magnet supplies the power for the electronics which transfers the measurement data to a receiver unit mounted on the engine crankcase [1].

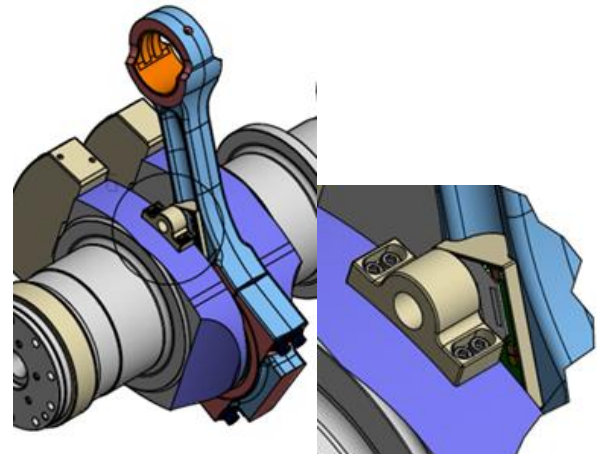


Figure 9. Design mock up of power train unit including Telemetric system / Detail of Magnet mounting

For an optimal measurement position 10 to 15mm deep drillings from the bearing side face have been machined 1.5mm underneath the running surface in the high loaded zone.

In addition to the energy-harvesting system and the positioning of the sensors, a main design focus has been a minimum impact on the structural integrity of the connecting rod, as well as easy system assembly. As shown in Figure 10, the system fits on the conrod with only minor additional machining (transition slot for the wires from bearing shell to electronics). Overall, the whole set up proves a general feasibility for future pre-serial / serial applications.



Figure 10. Connecting rod incl. bearing shell and mounted Telemetric system

## 6 SCE SYSTEM MONITORING AND VALIDATION

### 6.1 Rig set up and LEC testing environment

The complete single cylinder power unit as shown in the CAD assembly in figure 11 consists, from left to right, of the power unit, an intermediate shaft assembly and an active dyno sitting on a common base frame. The single cylinder engine was assembled at AVL and then installed on and connected to the test rig at the Large Engine Competence Center (LEC) in Graz in combination with an active dyno as well as external, controllable and conditioned media supply for fuel, air, coolant and oil. In figure 12 the interfaces for the external coolant as well as the various lube oil supplies are shown.

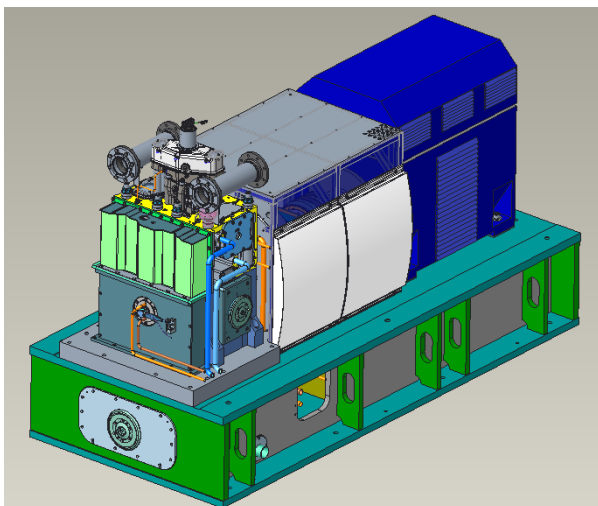


Figure 11. SCE and dyno assembly

To ensure and to measure the condition of the lube oil supply for the piston group (piston cooling jets) and the conrod big end bearing, the oil feeds to these are separated from the overall engine

lubrication system. Due to this setup, the temperature, pressure and volume flow can be adjusted and also measured for parameter studies.



Figure 12. Engine on test bed P1 at LEC incl. the lube oil and coolant interfaces

### 6.2 Engine start up & running in

To avoid any early failures by improper adaptation of tribological interfaces the engine was put through an extended run-in program to allow all components enough adaption time. In parallel the valve lash in operation was measured and the cold setting values were optimized in view of dynamic valve train conditions, maximum lift and sufficient wear reserve.

After successfully passing the run-in program a detailed performance and emission development test program was executed followed by a 50hrs durability screening test.

### 6.3 Bearing monitoring and verification

During operation, the condition of the complete engine was monitored by continuous monitoring of the overall friction and the plain bearing condition on top by an automated comparison of the bearing and bearing shell back temperatures with the target values.

The reduction of the lube oil supply pressure towards the BEB showed low sensitivity. The bearings maintain a hydrodynamic condition without excessive asperity contact as long as oil is supplied towards the bearing. As depicted in figure



13 the temperature gradient rises for low supply pressures. This indicates a further reduction of supply pressure lower than 1.5 bar is not recommended, as thermal instability might occur.

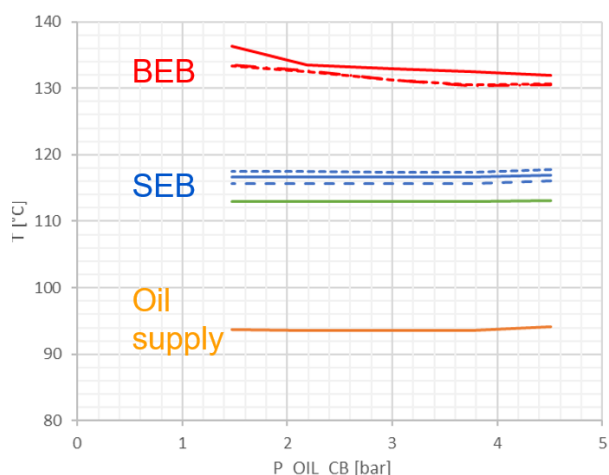


Figure 13. BEB and SEB back temperatures vs. lube oil supply pressure

#### 6.4 Post test Power unit inspection

At every change of hardware for different combustions system investigations all relevant components have been assessed and documented including the conrod bearings. The small end bushings did not show any indications of local overloading or lube oil starvation as visible in figure 14. Especially the high loaded edges don't indicate any signs of wear or material deformation / scuffing, due to the crowning of the bushing.

The conrod big end bearings showed minor signs from run-in but didn't show any signs of local overloading as shown in figures 15-17. A few traces from foreign particles could be observed at some inspections, but the bearings were able to embed them and there were no follow up damages on the overall engine.

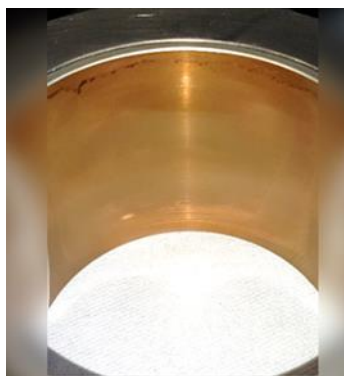


Figure 14. Excellent behavior of the small end bushing after max. BMEP tests (Miba 2A)

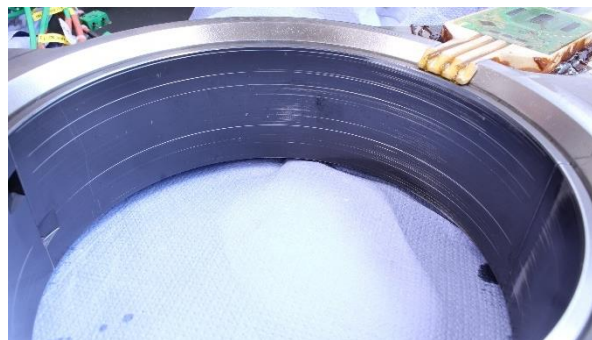


Figure 15. Big end bearing (Miba 6G incl. temperature telemetry) inspection after max. BMEP tests

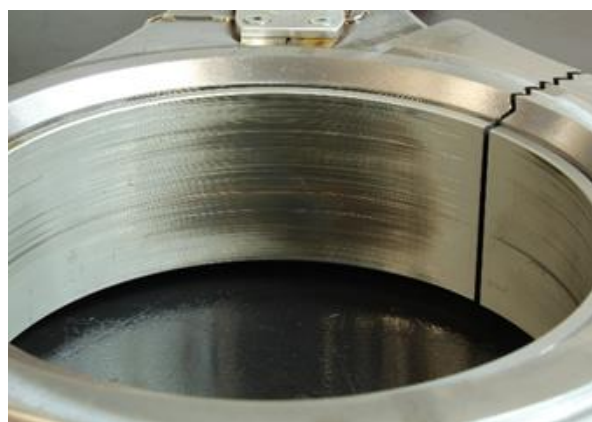


Figure 16. Big end bearing (Miba 3H) inspection after max. BMEP tests -



Figure 17. Big end bearing (Miba 4B) inspection after alternative fuel tests ( $H_2$ ,  $NH_3$ )

Overall an excellent adaption and wear behavior (as documented in the Figures 15 to 17) has been achieved for the different bearing types. For the Sputter bearing types 6G (AlSn20 / Synthec®) & 3H (SnCuSb) the test focus has been on the performance under high BMEP level. In contrast Miba 4B with the softer SnSbCu e-plated overlay, the functionality under medium load in combination with alternative fuels has been the main testing objective.

## 6.5 Simulation validation

After several hours of full load operation at 330bar firing pressure at different speeds and lubrication conditions the big end bearing and small end bush have been inspected for wear marks and run-in profiles (shown in the figures 14 to 16). The inspection revealed an excellent match of load distribution across the big end bearing width.

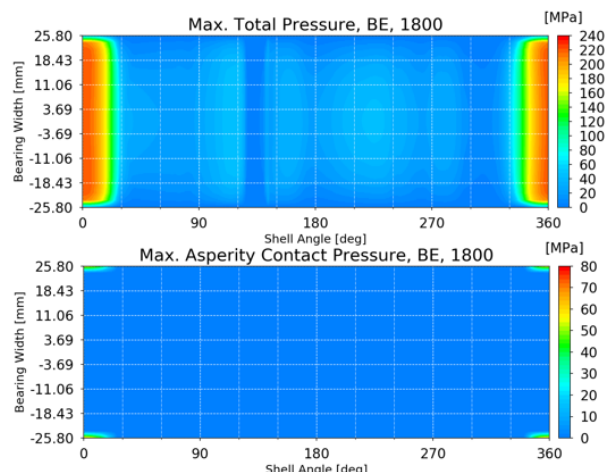


Figure 18. Big end bearing simulation results comparing to figure 16-17 [7].

For the small end bush the load is evenly distributed and the edges are clear from material deterioration or plasticity by local overloading leading to the conclusion that the simulated form shape meets the engine demands properly.

The essential part of the virtual phase that has been applied successfully is to anticipate the loading and required form shape to avoid reverse engineering requirements and drawing / hardware updates.

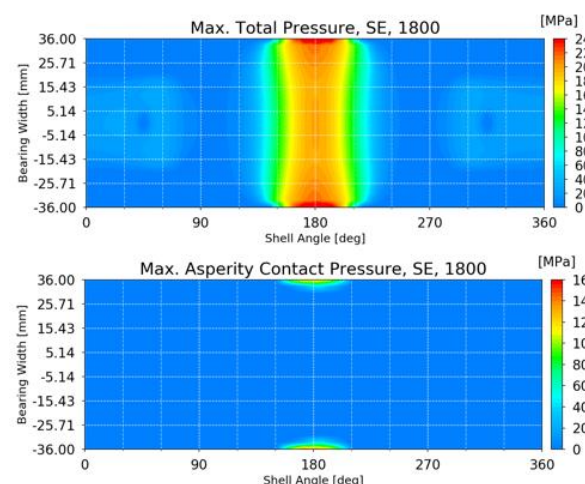


Figure 19. Small end bush simulation results comparing to figure 14.

## 6.6 Bearing Temperature

The BEB and SEB temperatures have been simulated upfront to predict the temperature and temperature distribution in the bearings under different operating conditions. Excite Power unit thermal slider bearing methodology (EHD+T) [4] has been used using different oil supply pressure levels and load scenarios of the engine. Figure 20 shows the temperature distribution on the bearing shell surface after stabilization of the temperature calculation. Locally the measured values under the same condition are shown. The given measured values are taken at the bearing shell back and therefore slightly lower.

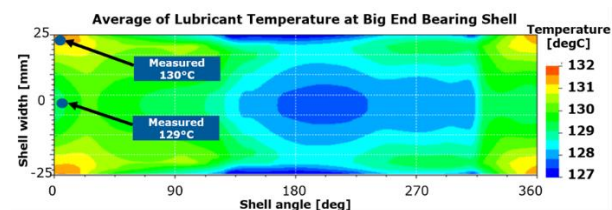


Figure 20. Big End Bearing simulated surface temperature under full load full oil supply condition compared to measured values [7].

Figure 21 shows the temperature development for different stabilized BMEP levels for 1500rpm and for 1800rpm. Measurement and simulation are within a few degrees of each other for bearing center and bearing side. This demonstrates the capabilities of predicting temperature in the bearing for different conditions. It is obvious that bearing temperature is driven more by sliding speed than by engine load for a well-designed bearing environment. At lower speeds the load shows more effect on bearing temperature as the load has direct influence on asperity friction loss.

At all shown conditions the supply temperature and supply pressure to the BEB has been held constant.

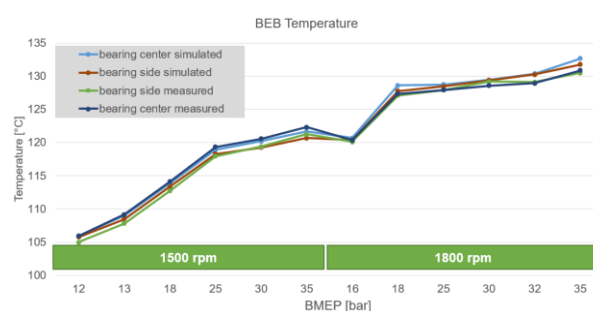


Figure 21. Big End Bearing simulated and measured temperature over BMEP for 2 engine speeds.

## 7 CONCLUSIONS

The joint project was set up to prove the following:

- Robust power unit design up to a high BMEP level of +35bar and PFP of 330bar with a power unit potential for further increase.
- The functionality of lead free BEB and SEB
- Validation and verification of the front-loaded analysis supported design, showing the capabilities of AVL & Miba
- Functionality of Miba's Telemetric system for the measurement of Conrod BEB temperatures powered by energy harvesting system
- Verification the bearing performance of the newly developed Miba bearing types 2A (for the SEB), 6G, 3H and Miba 4B under extreme load as well as alternative fuel combustion conditions
- Investigation of oil pressure sensitivity on BEB temperatures
- Engine testing and inspections indicate representative TbOs, however this has to be proven via DVP on an MCE engine level testing.

Overall, all the targets have been achieved. The SCE shows major potential for top efficiency in diesel as well as in Hydrogen or Ammonia combustion mode with no short-term influence on the mechanical behavior on the crank train. In addition, the functionality and robustness of lead-free materials for SEB and BEB has been shown.

## 8 DEFINITIONS, ACRONYMS, ABBREVIATIONS

**ICE:** Internal combustion engine

**BEV:** Battery electric vehicle

**FCEV:** Fuel cell electric vehicle

**SCE:** Single cylinder engine

**HSLE:** High speed large engine

**BEB:** Big end bearing

**SEB:** Small end bushing

**BMEP:** Brake mean effective pressure

**PFP:** Peak firing pressure

**MBD:** Multi body dynamics

**EHD:** Elasto hydro dynamic

**TbO:** Time between overhauls

## 9 ACKNOWLEDGMENTS

The research engine testing was performed as part of the COMET Large Engines Competence Center program and was supported by the federal government and the provinces of Styria, Tyrol and Vienna.

## 10 REFERENCES AND BIBLIOGRAPHY

- [1] Hager, G. 2019, A New Technological Approach to Onboard Bearing Condition Monitoring validation, Proceedings of 29<sup>th</sup> CIMAC world congress, Vancouver, Canada
- [2] Zorn. K, Bearing Challenges on High Performance Gas Engines, Proceedings of 29<sup>th</sup> CIMAC world congress, Vancouver, Canada
- [3] Offner G., Knaus O. 2013. Friction Power Loss Simulation of Internal Combustion Engines Considering Mixed Lubricated Radial Slider, Axial Slider and Piston to Liner Contacts, Tribology Transactions. 56: 503–515.
- [4] Lorenz N., Offner G., Jaitner D. 2021. Fast Thermal Heat-Up Simulation of Hydrodynamic Lubricated Journal Bearings. NAFEMS. Salzburg.
- [5] Estebanez, G. 2023. GHG Reduction on High Speed Large Engines, Proceedings of 30<sup>th</sup> CIMAC world congress, Busan, Korea.
- [6] ABAQUS. (2021), ABAQUS Theory Manual, Ver. 2021.
- [7] AVL List GmbH. (2022), AVL-EXCITE, Theory, Ver. 2022.2, AVL List GmbH. Graz, Austria.