Innovative piston technology for passenger cars and utility vehicles by KS Kolbenschmidt

Profound piston system expertise
Introduction

The major trends in state-of-the-art combustion engines, such as downsizing, supercharging and direct injection, intended to comply with required exhaust gas limits and to reduce fuel consumption and CO₂ emissions, remain drivers of innovation for new piston technologies. For modern piston systems, this means they must simultaneously comply with the demands for reduced friction, low weight and increased durability at maximum strain.

New nano-reinforced diesel alloys improve passenger car pistons

In 2012, KS Kolbenschmidt GmbH presented an alloy for diesel pistons in heavy-duty utility vehicle engines. The pistons have been enhanced by nano-phase, intermetallic separations and have made an impression with the formation of a particularly fine structure that results in considerably increased strength. In the meantime, we were able to transfer the experience gained from the new material and develop a diesel piston alloy for passenger cars. The alloy is a symbol of the company’s ongoing successful development of high-temperature aluminium materials for diesel pistons. We have already launched initial series development projects.

The objectives at the core of the new alloy that has been adapted to the specific framework conditions in diesel engine applications were increased thermal fatigue (ThF) and high cycle fatigue (HCF). For this purpose, we optimised not only the alloy composition but also the tool concept and the procedures.

The microstructure of the new alloy (Figure 1) is characterised by a higher quantity of intermetallic nano-phases compared with KS 1295, the previous standard alloy. This is based on the addition of special alloy elements with a lower solubility within the aluminium matrix.

**Figure 1:** passenger car diesel piston with remelted piston bowl edge made from the new KS309 NDA high-performance alloy

**Figure 2:** high cycle fatigue as a function of the thermal fatigue for the KS 1295 standard alloy and for the new diesel alloy

<table>
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<th>KS 309 NDA</th>
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<td>Material composition (Microstructure) +28% HCF</td>
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<td>Grain refinement due to HSDC +35% ThF</td>
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<td>KS 1295</td>
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<td>ThF cycles@T&lt;sub&gt;max&lt;/sub&gt; = 350 °C</td>
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Figure 2 illustrates the high cycle fatigue of the new alloy and KS 1295 (HCF@ T = 300 °C) as a function of the thermal fatigue (ThF@T_max = 350 °C). The combination of alloy modification, improved tool concept and optimised processing simultaneously results in a significant improvement of ThF values (+35 %) and HCF values (+28 %) compared with the KS 1295 standard alloy.

The results of ex-engine testing confirmed the results of in-engine testing. The service life of pistons made from the new alloy was 50 percent longer than the service life of pistons made from the KS 1295 standard alloy.

Local piston bowl edge remelting as a customised solution

In addition to using the new passenger car diesel piston alloy, KS Kolbenschmidt is currently transferring another utility vehicle technology to passenger cars: piston bowl edge remelting.

Piston bowl edge remelting has already become standard for utility vehicle pistons. The development of cracks at the edges of piston bowls is essentially caused by the varied thermal expansion characteristics of different microstructure components within a cast aluminium alloy. For this reason, the structural fineness that can be achieved is very important. The cast structure results from the solidification speeds achieved during casting. Despite ongoing development in material and casting technology it is very hard to fall below the applicable limits.

KS Kolbenschmidt’s solution to the issue was to develop a remelting procedure to apply to cast blanks. In this process, the sections under extreme load on the piston crown are remelted in a controlled manner, followed by completely processing of the piston bowl outline and compression surface. The resulting fine structure that is homogeneous around the remelting sections increases the thermal fatigue characteristics of the critical sections by up to 90 % (see Figure 3). The increased process stability in comparison to casting is an additional benefit.

The remelting procedure represents a customised solution that considerably increases the reliability and quality of diesel pistons. Engine testing results from KS Kolbenschmidt and from customers have confirmed the potential of the technology.

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Top performance and reduced consumption with passenger car steel pistons

Compared with aluminium pistons, modern steel pistons provide a robust solution solution for future supercharged diesel engines with specific engine performances in excess of 100 kilowatts per litre and ignition pressures beyond 200 bar. The focus during the transition to steel as the piston material lies not only on the realisation of increased performance, but also on the improved thermodynamic efficiency achieved with the steel piston and the potential reduction in friction resulting from a piston design that is geared towards steel materials.

Improvements in fuel consumption and emissions therefore add up to up to 5% depending on the application.

Almost all international car manufacturers are currently testing the passenger car steel piston as part of endurance runs. KS Kolbenschmidt was recently appointed to take charge of series development and the production launch is scheduled for 2014.

The patented KS Kolbenschmidt steel piston design consists of a single-part forged piston with supported ring zone that is characterised by very low groove deformation (Figure 4). With this concept, it is possible to safely comply with more demanding future requirements in terms of gas flow quantity and oil consumption.

LITEKS®-3 lightweight design and reduced friction for petrol engine pistons

Apart from the familiar piston-specific basic requirements, the development of modern petrol engines focuses on topics including reduced friction, increased mechanical and thermal resistance at a reduced piston weight, optimised secondary piston movement and optimised gas and oil sealing functions.

Figure 4: patented KS passenger car steel piston for reduced fuel consumption and increased reliability

Figure 5: new generation of LiteKS® lightweight design pistons for petrol engines made from KS309 high-performance alloy
The consistent ongoing development of the LITEKS® piston design up to the current third generation has enabled the weight advantage compared with the standard piston design to be increased to 28%. The new KS 309™ high-performance alloy provided the basis for this enhancement, in connection with further optimised casting technologies and the consistent adaptation of the design to the resulting material-specific benefits.

In order to reduce the weight, we brought casting tool technology to series maturity that represents recesses in the weight pockets of the ring zone for the first time. This technology was successfully launched in series production on the basis of the current LITEKS® design (Figure 5).

The friction output advantage at the skirt of the fired engine for this piston concept was verified by applying the floating-liner testing technology available to KS, and can be up to 46%! This potential is enabled through the implementation of a comprehensive package of measures to reduce friction, such as an asymmetrical definition of the piston skirt widths adequate to withstand the loads applied, reduced axial offset, increased clearance and functional, asymmetrically crowned skirt geometries (Figure 6) as well as the use of the new NANOFRIKS® piston skirt coating. The piston noise response was also verified and showed no disadvantages compared with previous designs.

**NANOFRIKS® – reducing friction and wear**

Modern engines and current piston designs are challenging the tribological load capacities of the piston skirt. The NANOFRIKS® skirt coating, developed by KS Kolbenschmidt to minimise friction and wear, fully complies with said requirements. We were able to apply the latest nanotechnology-related findings to this skirt coating for the first time.

![Figure 6](image_url)

**Figure 6:** LiteKS® concept with asymmetrically crowned skirt outline on the thrust and anti-thrust side to reduce friction

![Figure 7](image_url)

**Figure 7:** Floating liner measuring results for the skirt friction of NanofriKS® compared with LofriKS®
Tribometer tests confirm that the NANOFRIKS® coating reduces the dry-friction coefficient and wear by more than 50% compared with standard series coatings. To this end, NANOFRIKS® is setting new standards by featuring an adapted combination of nano particles, binding agents, solid lubricants and additives.

NANOFRIKS® therefore sustainably complies with the current customer requirements profile with respect to reduced consumption and high reliability as part of in-engine use (Figure 7). The successful series introduction of NANOFRIKS® at leading car manufacturers around the world emphasises KS Kolbenschmidt’s leading role in piston coating technologies.

STEELTEKS® – second generation of utility vehicle steel pistons for minimum compression heights

Run times are always longest in the truck and transport sector. In addition to the reliability that is necessary for complying with this requirement, the objectives are low emissions, maximum efficiency and hence low fuel consumption.

In contrast to friction-welded steel pistons, the patented Kolbenschmidt STEELTEKS® piston is produced from a single forged part. The development of this special design has enabled Kolbenschmidt to implement a completely new production method for mono block steel pistons.

We are currently working on further developing and extensively testing the STEELTEKS® piston in order to create a second, improved generation of mono block steel pistons.

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**Figure 8:** contact pressure distribution at the pin, rotational speed and friction loss within the piston pin bed in the utility vehicle steel piston module at 1,900 rpm, full load

Contact pressure and deformation of the piston pin at 370 degrees kW (max. gas force)

Upper side in the piston hub

Bottom side in the connecting rod eye
The extremely low compression heights enabled by this piston design amount to less than 50% of the cylinder diameter (Figure 9).

In the same way as for pistons that are friction-welded twice, we were able to transfer the benefits regarding friction, weight, wear and cavitation to this design.

**KS system expertise reduces emissions and fuel consumption**

In recent years, KS Kolbenschmidt has consistently built up expertise in designing, developing and producing systematically optimised piston systems.

We successfully operate a dedicated friction output test bench for passenger car applications that operates according to the floating liner principle in order to integrate the results into areas such as friction simulation.

KS develops complete piston systems for utility vehicles, consisting of pistons, piston rings, cylinders, pins and connecting rods that have been optimised with regard to friction and consumption. On a whole, the piston system optimised by KS Kolbenschmidt is characterised by friction values reduced by up to 18% at a constant, low oil consumption.

The friction at the piston pin represents a further friction component within the piston system. For this reason, KS Kolbenschmidt has determined the friction coefficient between pin, piston and connecting rod for various high-performance material combinations so as to integrate the results into the piston dynamics simulation (Figure 8). Piston pins were also coated and tested with diamond-like carbon (DLC).

Figure 10 illustrates the potential CO₂ savings of the system components within a passenger car diesel engine. The use of steel pistons and the optimisation of additional components within the assembly group allow for CO₂ savings of up to 4.5% compared with current standard aluminium piston systems.
Piston Systems
for Commercial Truck Applications
Introduction

Based on current market demand, diesel engine development has targeted the requirement for high power density and increased torque with low fuel consumption. Fulfilling high expectations regarding noise, driving comfort and reliability are certainly further essential goals.

The European emission regulations, Euro 5 and Euro 6, which are effective by 2009 and 2014 respectively, have accelerated the development of even higher performance injection and after-treatment systems. To satisfy these requirements, KS Kolbenschmidt is developing power cylinder systems with reduced weight and lower emissions along with reduced friction and excellent blowby characteristics. The integrated optimization of the power cylinder unit consisting of the piston, rings, liner, pin, and connecting rod, is an essential part of the system development at KS Kolbenschmidt. This sub-system integration relieves resources at the OEM and contributes to a reduction in development time and cost. This results in piston systems characterized by optimum performance, high reliability, and increased durability.

Layout and Reference Design

The expertise to design a new piston system is based on our continuously updated benchmarking data. According to the specific requirements of our customers, the piston system is examined, and suitable suppliers are rated to best meet the customers’ desired technical and commercial performance. As an independent system integrator, we select components from various capable suppliers according to our customer requirements regarding technological and commercial factors. However, for best technological performance and prototype logistics, we refer to our network of preferred component partners. For the requirements of future environmental legislation (Euro 6 and EPA 2010), we have created several pre-optimized reference designs which are used to begin customized development. For these reference designs, the required engineering phases, the functional optimization of component integration, and engine testing have all been completed. The reference designs are used as a starting point for the subsequent optimization of a specific system and its components by using finite element analysis, functional simulation, and engine testing with respect to emissions, fuel economy, and durability.

Fig. 1: Piston system components and their main contributions to system properties

Fig. 2: Piston system development

Fig. 3: Simulation of piston system behaviour regarding ring motion and oil film thickness
Design Optimization

The integration of the pre-optimized systems into the customized development begins by designing the components to meet the engine’s boundary conditions. The components are first optimized by individual FEAs which are later integrated into the engine simulation. The system analysis provides the correct boundary conditions for the next finite element iteration. The functional optimization is performed with the best simulation tools available today (see Fig. 3) to determine the system performance for specified operating conditions in this early stage of the development process. We conduct a comprehensive system failure mode effect analysis with all relevant process partners. In addition to the FMEA of the components, the system FMEA is used to summarize potential interface problems, define countermeasures and establish test procedures for further system verification.

To summarize, our analytical tools are utilized throughout the entire development phase to actively support system optimizations during engine and vehicle testing. Our tools help reduce development loops and time-to-market for each engine project. An example of successful system integration into a new 11 liter engine with respect to oil consumption, blowby and low friction by transferring demonstrator results is shown in Fig. 4. The blowby is decreased below the target level by introducing the KS monoblock steel piston. The oil consumption is further reduced by the application of an ultra-low oil consumption ring pack, and honing optimization at the cylinder liner. Applying the low friction rings, friction is optimized whilst still obtaining a substantial oil consumption reduction. Overall, the KS piston system addresses the challenging functional targets for this application under Euro 6 and US 10 legislation.

Project Management

Experience shows that customers value the transparent and structured project management which is the basis for successful integration of single components into a reliable system.

The KS in-house project management tool, KS OPUS, defines and coordinates all relevant interfaces between engine development at the customer and system integration at KS Kolbenschmidt, including all relevant component developments. To supply a perfectly tuned system from a single source to our customer, we at KS Kolbenschmidt have made strategic alliances to build a competent network of leading component suppliers.

In terms of technology, we closely monitor the latest progress, conduct joint R&D projects with our partners, and conduct continuous benchmarking in order to be in tune with the newest developments. These early technological activities are supported by our newly founded Innovation Center. After all, to perpetuate our successful track record we rely on customers that are satisfied in every respect.

Outlook

We view the relationship with our customers as a key element for success. Ongoing changes within the automotive industry require a cohesive effort among the suppliers to provide a technological integration of sub-systems. With our Piston Systems unit, we at KS Kolbenschmidt are positioned to address these challenges and view ourselves as a globally operating partner for the automotive industry. At Kolbenschmidt, we command the necessary resources and capabilities to supply our customers with the best possible performance, quality, and reliability in the form of the corresponding components: pistons, rings, connecting rods, cylinders, and pins. In addition, we routinely handle the necessary process and interface management between customers and suppliers. After all, the collective total is more than the sum of its parts. We do not rest on our success, but continuously strive for enhancements in efficiency. By including our own broad technological capabilities, we succeed in integrating commercially competitive sub-system components into functional and cost-optimized power cylinder modules.
New Materials and Processes
for Passenger Car Diesel Engine Pistons
Introduction

The development targets for today’s diesel engines cater to high performance and high torque while curbing fuel consumption. Additionally, exacting demands are made on noise reduction and ride comfort.

The European exhaust gas standards EURO 5 and EURO 6, which are coming into force in 2009 and 2014, respectively, are bound to accelerate the development of high-performing injection and exhaust gas post-treatment systems.

In order to meet the future requirements coming from the mentioned standards, KS Kolbenschmidt GmbH has developed a new generation of aluminum materials for pistons and a novel laser technology for local improvement of the thermal fatiguing characteristics of the material in the combustion chamber bowl zone. The optimization of the dimensioning and computation methods applied, along with improved piston cooling and the reduction of piston friction are features to be considered for every new piston development.

Thermal and mechanical piston loads

The aforementioned customer requirements prompt higher mechanical and thermal stresses acting on the piston. The demand for low weight coupled with geometric constraints (low compression height, small pin diameter) for peak pressures of 200 bar and beyond are the drivers for consistent further development of our aluminum materials and the search for new design solutions.

The pin boss design, refined pin bore geometry and pin geometry are the geometric measures at hand to boost the boss load capacity – however, with an impact on the bowl edge, because an improvement in the allowable load exerted on the boss invariably leads to a higher bowl edge load. Hence in each case a trade-off must be made between boss and bowl loads. To achieve a maximum contact surface between the piston pin and the boss, the piston-boss spacing is reduced by using a tapered conrod. High contact pressures between pin and conrod as well as the shape stability of the small-end conrod bore are setting limits. When all geometric possibilities are exhausted – such as the curved inner boss surface – the use of boss bushings is reasonable.

Fig. 1: Passenger car diesel pistons designed for high thermal and mechanical loads
to achieve a further increase in boss load capacity. This solution has been proven in mass production for many years. The changeover to lead-free bushing materials as prescribed by the EU End-of-life Vehicle Ordinance has been largely completed.

The second, especially critical, area of high-loaded state-of-the-art diesel pistons is the combustion chamber bowl. Future specific engine performance outputs of 70 kW/l and more will result in bowl edge temperatures exceeding 400 °C (cf. Fig. 2.).

The combination of thermal-mechanical fatiguing (TMF) and the high frequency fatiguing (HCF) resulting from the gas force may lead to cracking at the bowl edge or other areas of the bowl subject to high load. This requires improvement of the material characteristics.

**New material generation – V4**

Diesel pistons made of the new KS Kolbenschmidt alloy V4 are specifically suited to comply with the aforementioned requirements. The aluminum-based alloy will appreciably extend the product life in temperature ranges above 300 °C. This is made possible by a selectively developed alloy composition and a process-controlled microstructure adapted to the specific thermal and mechanical piston loads (cf. Fig. 3). Fig. 4 illustrates the improvements achieved with it in the bowl edge thermal shock test.

**New laser technology – local bowl edge remelting**

For especially high local thermal and mechanical loads at the bowl edge of diesel pistons, KS Kolbenschmidt has developed a hybrid remelting process where a zone subject to high load is remelted under controlled conditions by applying laser technology (Fig. 5).
This will produce an optimized, fine and homogeneous microstructure. This structure improves the thermal fatiguing properties of the critical zone by up to 60%. Further advantages are higher process stability compared to casting and improved surface quality for finishing. The laser remelting method is a tailored solution that allows a distinct increase in reliability and quality of diesel pistons to be achieved.

**Piston cooling – DynamiKS® – new piston cooling concepts**

For effective temperature control, pistons have a hollow annular cooling channel filled with oil through a nozzle installed on the crankcase. The oil will absorb heat and dissipate it upon leaving the channel. The position, and mainly the shape, of the cooling gallery significantly influence the temperature distribution of the piston.

This is the reason why KS Kolbenschmidt is continuously optimizing its cooling gallery designs. Today’s KS Kolbenschmidt standard is the ContureKS® cooling gallery with variable cross section that has already provided satisfactory service in millions of passenger car and utility vehicle diesel pistons.

The latest development, the DynamiKS® pump cooling gallery (Fig. 6), takes advantage of the piston movement dynamics to attain an increased oil throughput. The special, staged geometry, patent pending design imposes a velocity component on the oil in a circumferential sense during oscillation. The higher flow velocity substantially enhances the oil transport. Compared to ContureKS®, a temperature reduction of up to 20 °C is achieved at the bowl edge.

Both ContureKS® and DynamiKS® cooling galleries are produced cost-effectively using saltcore technology, a method tried and tested for more than 40 years. The DynamiKS® pump cooling gallery is already service proven in mass production, being applied for maximum specific engine performance outputs.

Further solution approaches geared to improving piston cooling have been analyzed at KS Kolbenschmidt in the advanced development phase. To this end, piston temperatures for a typical passenger car diesel engine with different cooling gallery geometries, in combination with one and two cooling oil nozzles, were measured and compared. The twin-nozzle concepts especially yielded a further distinct boost in cooling efficiency /1/.
Outlook

The ring carriers in a piston can be used for supporting a specific cooling gallery which consists of a specific-shaped plate welded tight to the ring carrier. This design is particularly appropriate for pistons where high loads require that they have a ceramic fiber reinforcement – FibreKS® – in the piston relief zone. The Squeeze-Cast process needed for this piston type requires fewer cast-in parts but the gallery geometry must be appropriate for the high pressures inherent in this process. Pistons of this design have already demonstrated their functionality in many engine runs.

A subject which has again and again been in the focus of discussion is the use of steel pistons in passenger car diesel engines.

For this market, it should be considered that the assets of steel pistons such as reduced installation clearances, low consumption figures, long service life have to be harmonized with the customer demands for low emission levels, light-weight, efficient cooling and a competitive price.

The latest results of various advance development projects demonstrate that this is viable, and the foundations are laid for the application of this technology in mass production. Fig. 7 shows a cross section through a KS Kolbenschmidt developed passenger car steel piston for diesel engines of low compression height.

As one of the leading international piston manufacturers, Kolbenschmidt Pierburg is in a position to deploy the synergies between the areas of large pistons, utility vehicle and passenger car pistons for the benefit of each and every one of these product ranges. In doing so it can draw on the wealth of experience gathered from local development projects worldwide at the development centers and plants in Europe, North and South America as well as Asia.

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**Figure 1:** passenger car diesel piston with remelted piston bowl edge made from the new KS309 NDA high-performance alloy

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Figure 2 illustrates the high cycle fatigue of the new alloy and KS 1295 (HCF@ T = 300°C) as a function of the thermal fatigue (ThF@Tmax = 350°C). The combination of alloy modification, improved tool concept and optimised processing simultaneously results in a significant improvement of ThF values (+35%) and HCF values (+28%) compared with the KS 1295 standard alloy.

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The remelting procedure represents a customised solution that considerably increases the reliability and quality of diesel pistons. Engine testing results from KS Kolbenschmidt and from customers have confirmed the potential of the technology.

Figure 3: increased thermal fatigue strength resulting from piston bowl edge remelting (Tmax= 350 °C/Tmin= 175 °C)
Top performance and reduced consumption with passenger car steel pistons

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LITEKS®-3 lightweight design and reduced friction for petrol engine pistons

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The friction output advantage at the skirt of the fired engine for this piston concept was verified by applying the floating-liner testing technology available to KS, and can be up to 46%. This potential is enabled through the implementation of a comprehensive package of measures to reduce friction, such as an asymmetrical definition of the piston skirt widths adequate to withstand the loads applied, reduced axial offset, increased clearance and functional, asymmetrically crowned skirt geometries (Figure 6) as well as the use of the new NANOFRIKS® piston skirt coating. The piston noise response was also verified and showed no disadvantages compared with previous designs.

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Figure 8: contact pressure distribution at the pin, rotational speed and friction loss within the piston pin bed in the utility vehicle steel piston module at 1,900 rpm, full load
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Figure 10 illustrates the potential CO₂ savings of the system components within a passenger car diesel engine. The use of steel pistons and the optimisation of additional components within the assembly group allow for CO₂ savings of up to 4.5% compared with current standard aluminium piston systems.

**Figure 9**: STEELTEKS® mono block utility vehicle steel piston design enables minimum compression heights

**Figure 10**: CO₂ savings in a passenger car diesel engine developed in a customer project