The New BMW Inline Six-cylinder Composite Mg/Al Crankcase

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Abstract

BMW's new inline six-cylinder spark-ignition engine sets new standards in specific power, weight and fuel consumption. The fundamentally new design is based on the latest technologies, such as an electric coolant pump, a further development of BMW's VALVETRONIC variable valve timing and, as an additional major innovation, the composite magnesium-aluminum crankcase. The engine will be installed in virtually all BMW vehicles and used worldwide.

The engine crankcase design concept, the alloy development programme and the relevant process aspects will be addressed. Critical for the development was to balance in the Mg-alloy the mechanical properties on one hand and castability on the other hand, with each of the properties having a minimum requirement to comply with the design and manufacturing concerns. Due to the compound concept chosen, the interface posed challenges to both the production and design. A set of novel techniques has been used to cope with these tasks.

Introduction

More than 70 years ago, BMW launched its first car with a six-cylinder engine – an inline six-cylinder spark-ignition unit. The laws of physics have blessed this engine layout with ideal characteristics, and this uncompromised construction principle, with its legendary silky-smooth running, has remained in use for many years. More than ever before, luxury-class cars are expected to set the standard in terms of excellent performance, driving comfort and low fuel consumption. To satisfy these requirements in the best possible way, it was necessary to design a completely new engine to replace the existing inline six-cylinder spark-ignition engine, which had been in production for about 15 years.

To achieve the project's goals, a development containing a large number of trend-setting innovations was started – solely maintaining the inline six-cylinder construction principle. BMW's proven VALVETRONIC system was developed further as a technology for reducing fuel consumption. Fundamentally new technologies, such as the composite magnesium-aluminum crankcase and the electric coolant pump, help to achieve the attributes of low weight and efficiency. As before, production of the new inline six-cylinder engine will take place at two engine plants. The construction of a new engine plant as well as the completely new concept behind all the equipment used for mechanical processing and the assembly lines provided an important degree of freedom when working out the engine concept. The unmachined parts for the composite magnesium-aluminum crankcase and the cylinder head come from the BMW light alloy foundry, which also carried out the process development for these components.

The chosen engine concept forms the basis for a family of engines, which permits the modular production of different displacements, power outputs and emission variants. The market launch took place in September 2004 in the form of the 3.0 l VALVETRONIC engine for the BMW 630Ci. The new inline six-cylinder spark-ignition engine will subsequently be used in virtually all BMW vehicles.

Development goals and concept definition

A new engine must be better than its predecessor in every respect. The most important product characteristics were consequently defined as follows:

- ⇨ Increasing torque at lower engine speeds, as well as definite increases in the power output and the usable engine speed range.
- ⇨ Significantly reducing fuel consumption in all markets, regardless of specific fuel qualities and regulations.
- ⇨ Reducing weight – in spite of higher specific power output and the additional technology used for reducing fuel consumption.

In short, **"stronger, lighter and more economical"** was the formula governing the requirement specification for the new inline six-cylinder spark-ignition engine, Fig. 1.

Figure.1: *View of complete engine*

Safeguarding the robustness of the concept for future strategic requirements like dynamics leadership, fuel consumption reduction and emission targets sets the frame for a completely new engine design including a wide range of innovations aimed at achieving the ambitious set of targets.

Efficient dynamics – increasing the power output while at the same time reducing weight and fuel consumption – debars enlarging the engine displacement. To create a solid basis for high specific power outputs and high engine speeds as well as to further optimise the characteristic running smoothness, a bedplate construction was chosen for the basic engine.

The requirement for a considerable reduction in fuel consumption is satisfied mainly by BMW's proven VALVETRONIC concept, that has been further developed for the new engine. Re-configuration of the cooling system permitted the use of an electric coolant pump, which makes a noticeable contribution to reducing fuel consumption and increasing power output.

Lightweight construction is to be found throughout the engine, starting with the crankcase – the heaviest single component. The world's first composite Mg/Al crankcase is a fundamentally new technology that forms the basis for a significant reduction in weight. A series of further weight-saving construction measures helps to achieve the ambitious goal of reducing engine weight by 10 kg, while clearly increasing its range of functions.

The harmonious overall design and consistent use of advanced simulation methods allowed the engine to be developed to production readiness in 36 months, with two construction groups. The consistency of the data obtained from the parametric CAD system allowed it to be used comprehensively both in simulation and production environments and even for the construction of operating and testing equipment. Significant factors in achieving these goals included close collaboration between specialists from Development, Production, Service and Controlling, early involvement of suppliers in the development process and stringent project management.

Cylinder block and crankcase

The world's first composite Mg/Al crankcase is a fundamentally new technology and the basis for a significant reduction in weight. This amounts to 24% compared with the equivalent aluminum crankcase.

Due to the properties of magnesium, it is not possible to consider a simple substitution of materials. With about 30% less density, its modulus of elasticity is also smaller by about the same percentage. Furthermore, magnesium is not suitable for use as a material for running surfaces or for channelling coolant. Another limitation to freedom of design is magnesium's low creep resistance, especially at temperatures above 120°C which simply cannot be avoided in the cylinder block and crankcase.

However, these conflicts can be resolved by intelligent combining of materials in a composite construction. Initial investigations into achieving high levels of all-round rigidity revealed that a bedplate design offered the greatest potential and would more than compensate for the smaller modulus of elasticity.

The cylinder running surfaces, the cooling water circuit, the main bearings with their bolted fastenings and the cylinder head studs are integrated into what is initially a separate component known as the *insert*. The insert is made from a super-eutectic aluminum alloy and recast with Mg in a die-casting process. The result is the basic crankcase blank in composite form. This can only be achieved with an open deck, which is another important design feature.

The insert contributes a significant proportion of the rigidity and strength of the composite crankcase, with the surrounding Mg casting being used for the sections that help to achieve maximum weight reduction. Particular attention was paid to the clamping effect between the insert and recast, through positive coupling in the macro area, Fig. 2. This ensures the transmission of all forces at all working loads. In addition, a partially intermetallic boundary layer between the Mg recast and the Al insert guarantees the sealing function.

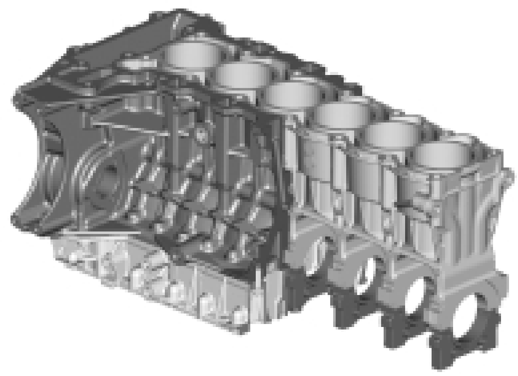

Figure 2: *Section crankcase and bedplate*

The engine mountings, all attached components and auxiliaries are bolted to the Mg recast. Functional integration directly into the crankcase of most of the holders for the auxiliaries is particularly advantageous. The result is a highly rigid and therefore acoustically excellent connection, with a lower overall weight.

The bedplate, Fig. 2, is also designed as a composite component and manufactured by high pressure die-casting. Sintered steel inserts are used to absorb the main bearing forces, while the rest of the structure is again made from magnesium. The bedplate is positively locked to the upper section of the crankcase with bolts.

To guarantee operationally threaded connections in magnesium for the lifetime of the engine, it is necessary to use aluminum screws. This minimises loosening caused by heat and avoids contact corrosion. There is also a weight advantage compared with steel screws.

Alloy selection and development

KEY DESIGN FEATURES AND MATERIAL PROPERTY REQUIREMENTS

In an engine block design, a multitude of different objectives need to be satisfied by the material/design combination next to the production constraints. One set of objectives related directly to the engine block operation is the functional requirements including the noise vibration harshness (NVH) and the aspect of durability. The NVH aspect defines the stiffness requirements on the overall engine block in combination with the material compliance; hence this is one of the subjects to be addressed first. For the highly loaded volumes in the component, such as the main bearing area and cylinder head bolt engagement, the static properties (Y.S.) are of importance. For the material volumes with cyclic loading, i.e. engine mount supports and bolted ancillaries define the requirements on material endurance capability. Overall, all the different requirements need to be balanced, also against the maximum operating temperature. For the compound design concept as described in the previous chapter, some minimum material property requirements were defined in the early stage of the concept design guiding the material selection process.

As the standard magnesium HPDC alloy AZ91HP does not exhibit sufficient creep strength in the target design temperature range of up to 150°C, it was necessary to select and develop an alloy to compromise between the required mechanical properties, in particular resistance to creep and fatigue, and castability. At the beginning of the project, commercial alloys from different material suppliers were investigated with regard to their mechanical properties and castability. The focus was on static, endurance and creep properties in the target temperature range. The creep properties were assessed using multilevel tensile tests with variation in both load and temperature forming the basis for simple creep models used in the numerical FE analysis of the structure. In addition, bolt load retention (BLR) tests were performed on components. The castability was evaluated on the basis of casting defects, hot cracking and die sticking tendency. From this initial alloy screening the potential of the different alloy systems was evaluated, with the AJ (Mg-Al-Sr) ternary alloy system of Noranda [3] showing the most promising potential with regard to the design and the manufacturing requirements. The initial AJ52x alloy was further developed with regard to improved castability.

After this selection, a massive in-depth material investigation programme was started to establish the required thermophysical and mechanical properties to provide the necessary input for both process and design analysis. Concurrent microstructrural analysis supported an in-depth understanding of the alloy.

METALLURGICAL ASPECT OF THE AJ ALLOY SYSTEM

The microstructure of Mg-Al-Sr alloys is characterised by primary a(Mg) dendrites and one or more second phases at the grain boundaries and in the interdendritic regions. The second-phase morphologies are lamellar, divorced eutectic, or massive. The aluminum and strontium contents of the alloy have a strong influence on the relative volume fraction of the various phases [4]. Based on the microstructure, the alloy system can be divided into three groups.

Figure 3: *SEM micrograph of die cast AJ – alloy with the 2nd phase precipitates*

The Mg-5Al-2Sr (AJ52x), the first-generation alloy formulation, has shown a superior creep resistance and excellent high-temperature properties. It was proposed that the creep resistance of AJ52x is related to the low aluminum supersaturation of primary magnesium and the absence of the $Mg_{17}Al_{12}$ phase due to the precipitation of high-melting-point Al_4Sr and $Mg_{13}Al_3Sr$ phases (see Fig. 3, 4).

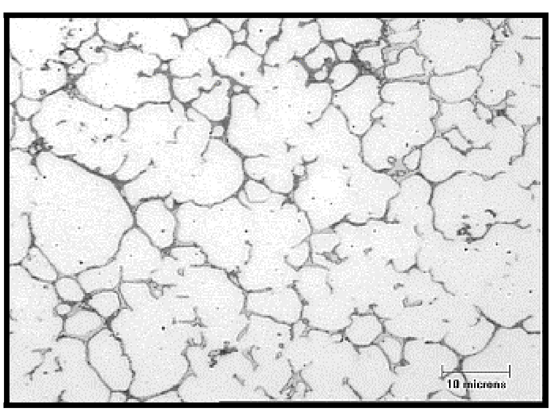

Figure 4: *Optical micrograph of a die cast AJ52x alloy (from [5], ©SAE).*

The Mg-6Al-2Sr (AJ62x) offers more advantages: improved die castability without significant degradation of the creep resistance and high-temperature properties [4]. Aluminum was added to improve castability and room-temperature tensile properties. The strontium content was also raised to avoid any precipitation of $Mg_{17}Al_{12}$. The Al_4Sr is found in a well defined lamellar-eutectic morphology (see Fig. 3, 5). As for AJ52x, the aluminum supersaturation is low, which offers a good creep resistance.

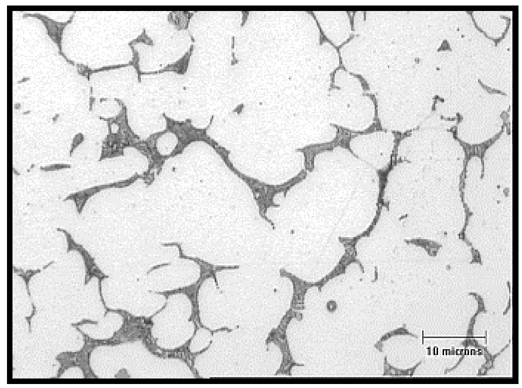

Figure 5: *Optical micrograph of a die cast AJ62x alloy (from [5], ©SAE).*

A low strontium version (AJ62Lx) was formulated to slightly increase the dissolved aluminum and, therefore, increase the tensile properties. The excess aluminum leads to the precipitation of $Mg_{17}Al_{12}$. However, the presence of Al_4Sr-a(Mg) eutectic phase offers a significant creep resistance up to 150°C.

The AJ alloys are characterised mainly by a low Al-supersaturation in the primary magnesium dendrites and the precipitation of a lamellar Al4Sr-a(Mg) eutectic in the interdentritic/grain boundary region. The effect of the aluminum and strontium contents on the microstructure is clearly visible in figures 4 and 5.

ALLOY OPTIMISATION APPROACH

The main task of the alloy optimisation work was to balance the mechanical properties required for the Al-Mg composite crankcase design regarding function and durability with the HPDC casting process. This approach is schematised in Fig.6. The goal is to specify the limits in strontium and aluminium, which offer (1) a robust operating window for HPDC of the component and (2) high temperature performances above the limits specified for the mechanical design. The approach requires a good understanding of the impact of chemical composition on the mechanical properties, mainly BLR as this is close to the design of bolted joints.

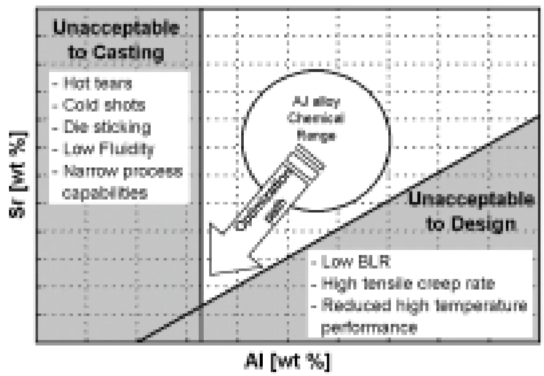

Figure 6: *Diagram of the alloy optimisation approach for the Al/Mg composite crankcase design, (from [5], ©SAE).*

For a given manufacturing process (e.g. pressure die casting), the aluminium and strontium contents are the governing variables that influence the microstructure. In turn, the microstructure, temperature and loads influence the mechanical properties of the alloy: BLR, tensile properties and creep resistance. The most reasonable way to determine these relationships with the amount of parameters involved is using multivariate analysis.

The effect of multiple factors (or variables-X) on the material response (property-Y) can be understood using multivariate analytical tools, namely partial least squares projections to latent structures, or PLS. The major advantage of PLS analysis is the ability to work with poorly structured dataset not generated by design of experiments (DOE) techniques, which is generally the case for the die casting process.

In a first step, the bolt load retention test (BLR) results from samples with different chemical compositions and various testing conditions (initial load and temperature) were used to generate the datasets for PLS analyses. The PLS model of the retained stress shows good predictability within the range of interest of the AJ alloy system. The alloy model was then used in conjunction with synthetic prediction sets to assess the risk to have a retained stress lower than given limits related to the aluminium-magnesium composite crankcase design. The synthetic prediction sets were generated using the convolution of the AJ ingot casting process capabilities and the crankcase HPDC process capabilities.

In a second step, in order to quantify the risk of not achieving the design targets, a risk analysis using the PLS model was done. The risk is evaluated using a statistical distribution of the chemical composition (for both aluminium and strontium) based on the convoluted process capabilities (variation in ingot composition and component composition). The alloy chemistry is then adjusted to minimise the risk to an acceptable level.

The AJ ingot casting process capability was determined during several weeks of production of ingots with an industrial casting line. During this production campaign, the chemical composition of each batch was recorded and, then, the average and standard deviations were calculated. The process followed a normal distribution for both aluminium and strontium.

The crankcase HPDC process capabilities were determined using chemical composition mappings. The composition was determined at various locations of the component. The average of several crankcases led to a good evaluation of the segregation within the part. Due to the intricate design, the aluminium and strontium tend to be different from one location to the other. It was noticed that the distributions of aluminium and strontium are strongly correlated. Basically, the ratio of strontium over aluminium (in wt.%) is identical to the Sr/Al ratio measured in Al_4Sr phase. This observation can be related to the variation of the volume fraction (or weight fraction) of Al_4Sr phase in a matrix of primary α-Mg. Since the Al and Sr contents of the α-Mg are much smaller than in Al_4Sr, the change in Al and Sr of the bulk alloy is directly related to the Al_4Sr content in the analysed volume. Therefore, the ratio of Sr/Al should be close to the one of Al_4Sr. A schematic of the alloy chemistry composition as generated using a standard ingot casting process capability (white circles) convoluted with the segregation in the engine block (black circles) is given in Fig.7.

The prediction set is used to calculate the retained stress after 1000 hours using the PLS model. The results are then illustrated in a normal probability plot and the risk of being below a specified limit can be evaluated. Figure 8 shows the normal probability plot of the retained stress after 1000 hours with 40 MPa initial stress at 150°C. As an example, the risk of being below 30 MPa retained stress is 0.001 (0.1%).

If the prediction set gives high probability of being below the target retained stress limit, the centre point of the ingot distribution is modified to reduce the probability to an acceptable level.

This process was iterated until the probability reached the acceptable level and, then, the alloy composition was considered optimised.

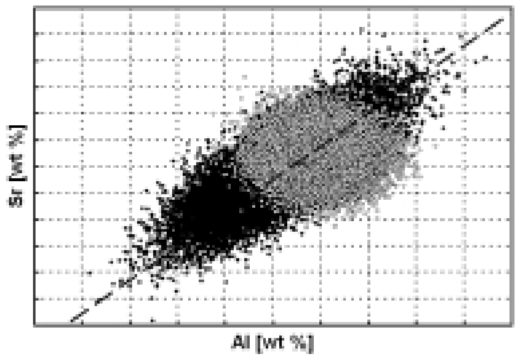

Figure 7: *Diagram of the alloy chemistry composition as generated using a standard ingot casting process capability (white circles) convoluted with the segregation in the engine block (black circles) (from [5], ©SAE).*

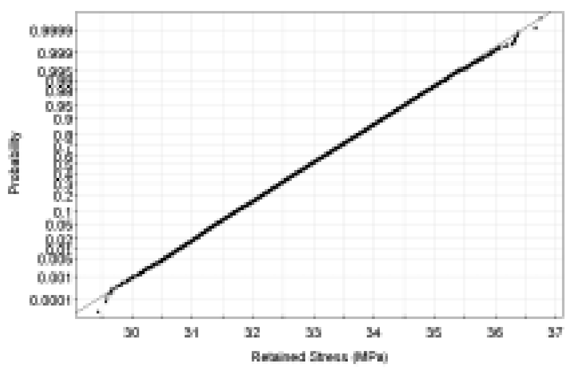

Figure 8: *Normal probability plot of the retained stress, after 1000 hours at 150°C with 40 MPa initial stress, using a convoluted chemical distribution (from [5], ©SAE).*

Next to the BLR tests, which are closest to the design aspect of bolted joints into Mg, other tests have been performed. Pure tensile relaxation tests performed for a variety of initial load and temperature conditions and chemical compositions fit into the prediction model of the BLR tests.

The full details are given in [5]. In addition, the expected precipitation of 2nd phases was predicted using thermodynamic modelling. The creep testing under tensile, compressive loading, relaxation testing and the BLR testing provided the input for material models used in the FE-analysis to design the bolted joints of ancillaries, bedplate and oil pan and secure sufficient contact pressure.

To minimise the BLR loss, to prevent contact corrosion and to minimise the thermal fatigue in the threaded area in the bolted joints, the AL bolts were introduced as new fastening technology.

The predictions from FE analysis were confirmed by component testing on bench tests using instrumented bolts and a variety of engine tests under different endurance programmes using ultrasonic length measurements of the Al-bolts up to 1200hrs of operating time. The base material creep testing included test times up to 5000 hrs.

MECHANICAL PROPERTIES

For the mechanical property determination, a major multi-year joint test programme was defined to provide data to understand the alloy in terms of mechanical performance. Samples were from separately cast specimens and machined from the HPDC engine blocks after final heat treatment to different chemical compositions. The mechanical test programme covered standard tensile testing, fatigue testing at different temperatures (RT, 120°C, 150°C) and R-ratios, creep-fatigue interaction test including different load cycle shapes, R-ratios and temperature and crack propagation testing. Notched specimens were used to address the notch sensitivity aspect. Details of the test procedures and part of the test results are presented in [6].

The results were used to evaluate the design using extensive finite element analysis of the engine block under in-service condition. In addition, component durability testing was done on both test bench and in full vehicle testing with instrumented engine blocks to confirm the predictions.

Production process development

In addition to the development of the casting process for the insert, which is manufactured in low-pressure die-casting from difficult-to-cast hypereutectic AlSi17Cu4Mg and the development of the composite casting process – high-pressure-die-casting, AJ62 – represents the guarantee of a stable, large-scale bonding and its testing the greatest challenge.

Due to the extremely similar solidus temperatures of aluminium and magnesium, during composite casting of an insert without any further surface treatment there arises a metallic bonding layer of three layers, comprising aluminum insert, reaction zone and magnesium cast. The reaction zone comprises the elements of the two compound partners. Due to the mixture of aluminium and magnesium and the secondary elements of Cu, Si and Sr, extremely brittle phases arise. In addition, there are in the reaction zone primarily rigid Si particles which have the effect of inner indentations. During mould filling, erosion of the insert surface occurs in some areas due to the hot molten metal which flows by.

The resulting accumulation of aluminium and copper in magnesium results in a worsening of the creep resistance / corrosion properties.

The metallurgical bonding is stressed by high loads which originate during the solidification and the cooling down from ejection temperature after the hpdc process to room temperature due to the different thermal expansion coefficients of aluminum and magnesium.

Due to this load, the connection zone tears. This results in oil leaks from pressurised oil-conducting channels which, due to the construction, penetrate the connection areas to outwards. Furthermore, a change to the connection following honing of the crankcase results in a shift of stress and, thus, to elastic distortions in the area of the cylinder faces, which leads to increased oil consumption and increased wear and tear.

In order to meet the functional requirements of a large-scale, stable bonding, it was necessary to increase the ductility of the connection layer and to isolate the Si particles and the elements retained in the insert, undesired in the magnesium, compared with the reaction zone / the Mg molten metal. This is achieved by means of an additional layer.

Before the actual coating is carried out, the insert is fully-automatically blasted with corundum. For reasons of corrosion and roughness, a considerably more economical blasting method with steel granules accelerated by spinner gates could not be realised.

Due to its low density and high abrasiveness, the corundum can not be accelerated by means of spinner gates. It has to be blasted with injector jet nozzles and compressed air onto the insert. Preliminary tests have shown that a minimum roughness of R_z=60-80µm is necessary in order to guarantee the layer adhesion of the connecting coating.

Furthermore, the high specific surface via the corundum injector jets of the inserts is necessary for the coating adhesion and the later connection in the cast state.

Following blasting, the coating is carried out within a precisely-defined period of time in order to prevent an oxidation and soiling of the blasted insert, by means of arc wire spraying.

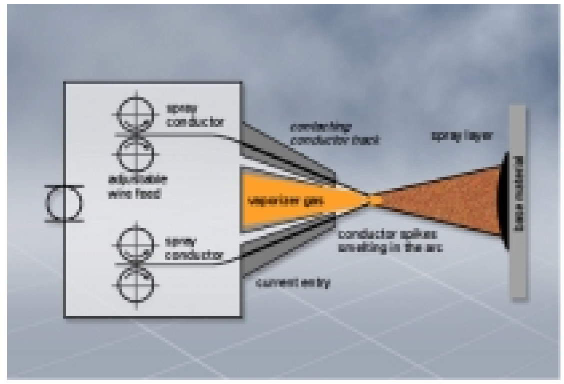

Figure 9: *Sketch of the arc spraying process*

In the arc wire spraying depicted in figure 9, two AlSi12 wires are supplied via a bundle of hoses similar to the inert gas welding. The wires are supplied with electricity via rolls or nozzles. From a certain distance, an arc lights and the wire material is liquefied. By means of compressed air, the metal drops are accelerated and sprayed. By means of the high metal temperature of up to 5,000°C and the high velocity of up to 300m/s of the drops upon striking the surface to be coated, a porous, rough layer with a very high specific surface, results.

Figure 10: *Arc spraying process*

The coated insert is pre-heated in a throughput furnace with recirculating air heating to a preset temperature. Right at the start of the process, the insert is given to the robot. During the entire insertion, the temperature is monitored online. This temperature control is decisive in order to guarantee, firstly, the quality of the connection between magnesium and aluminium and, secondly, to minimise the deviating dimensions caused by the thermal expansion of the insert. A decisive factor in casting the insert is the effective support of all cavities such as the cylinder bores and the water cooling jacket. This support can only be carried out by means of precise coordination of the tool to the insert geometry in a warm state. If the gap between the insert and the mould is too small there is local overlapping, the process-safe insert onto the mould would not be possible. However, if the gap is too large, severe deformation is the result, and thus also a deviating dimension or the destruction of the brittle AlSi17Cu4 insert.

Figure 11: *Inlaying of the insert in the hpdc-die with robot*

Following insertion, the mould is closed and approximately 30kg magnesium (AJ62) is pumped into the shot sleeve at about 700°C. The actual filling process is carried out in 3 phases, which is standard for die-casting. In the first phase, the air is displaced from the shot sleeve and the metal is conveyed to the ingate. In the second phase, the actual component filling is carried out at approx. 7m/s plunger velocity in about 65ms. The shrinkage deficits are minimised in the 3rd phase by means of a pressure of approx. 950bar. After about 18s, the mould is opened and the rough crankcase is unloaded. Like the insert, the crankcase is labelled by means of a data matrix code. In addition to the process parameters of the die-casting process, all data of the insert, such as casting parameters, date, results of the quality controls, spraying and coating parameters, are stored according to the component in a database.
Following labelling, the crankcase is roughly deburred in two fully-automatic individual stages. In the first stage, the vacuum channels, coarse division springs and the overflows are removed. In the second stage, the gate system is separated. Due to the easy flammability of magnesium chips, especially during the high temperatures immediately after removal from the mould, no standard sawing method can be used here. The shear cutting methods which have been used until now are also unsuitable due to the uneven cutting force which results in a high load on the connection layer. These high loads occur at a point in time in which the bonding layer's strength is still low – due to the temperature – and at which the internal stresses are already present at a high level due to the cooling-down process. Thus, a method had to be developed with which the casting system can be removed from the cast part such that no chips arise and there is no exertion of force on the cast part.

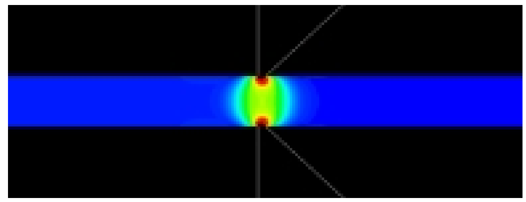

Figure 12: *FEM simulation of the wedge cutting process*

Following appropriate preliminary tests [7], the casting system is now removed by means of the cutting with two approaching blades process. The ingates on both sides of the crankcase are cut in a power-controlled way by means of wedge-shaped cutting of both sides. Due to the wedges' entry into the material, extremely high tensile stresses arise between the tips, see figure 12. The ingates break before the material is fully cut through. The force is limited to a very small part of the ingate.

In order to carry out standard non destructive tests on the connection layer, the standard tests usually carried out in order to ensure quality in the casting area, such as X-ray, ultrasound and computed tomography, are unsuitable since the internal cracks and detachments of the connection layer due to the increased thermal expansion of the magnesium and the associated shrinkage on the insert, no discernible cracks have to be present on the insert.
For the non destructive testing of the bonding layer, a method from the field of aviation and space technology / plastics testing, from ultrasound-stimulated lock-in thermography has been assumed and further developed. The crankcase is stimulated with a sinusoidal US-Burst. The waves spread chaotically in the component. At each imperfection in the connection area, the US waves cause a relative movement of the surfaces. The resulting friction heat penetrates through the component to the surface and is recorded by an ultra-precise thermography camera. Due to the cyclical stimulation, an equally cyclical temperature variation arises on the surface of the component. To filter the interferences this is evaluated

according to phase shift (temporal shift between stimulation and temperature signal) and according to temperature amplitude.

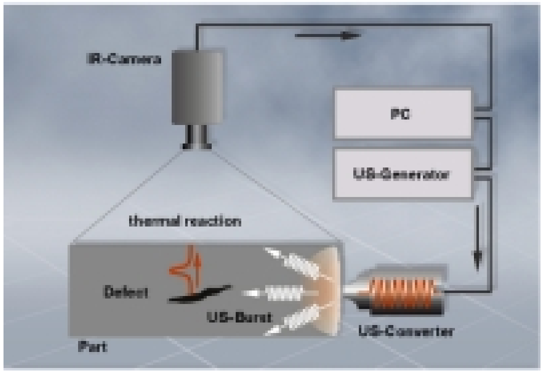

Figure 13: *Schematic illustration of the us-lock-in-thermography*

The evaluation of the thermography data is represented in figure 14 according to the amplitude. The light areas depict the delaminated areas of the connection

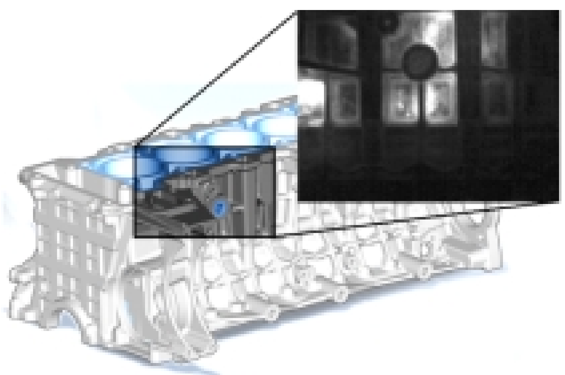

Figure 14: *Result (amplitude) of the us-lock-in-thermography*

The quality of the connection can be quickly and reliably tested using this method. It was only via the use of the US-lock-in thermography that a development of this casting process with regard to connection quality was possible.

In addition to the connection testing, the crankcases are subjected as standard to an X-ray test and, following thermal treatment and pre-processing, a density test.

Conclusions

A careful balancing of the mechanical properties with emphasis on both creep and fatigue material properties next to the castability process capability was achieved with the alloy optimisation as described above. With the introduction of the Mg-Al composite crankcase design in the new I6 engine, it is demonstrated that the AJ62A alloy has the capability to sustain such a severe application. With arc spraying as surface treatment and an optimised temperature controlling during the hpdc-casting process, it was possible to achieve stable bonding between aluminium and magnesium over a lifetime. A new testing methodology has been adapted for quality check purposes. With these ultrasonic lock-in thermography, the processes in production can be controlled.

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