Press release

Porsche develops innovative manufacturing process for highly-stressed drive components with Mahle and Trumpf

3D printing technology optimises pistons for the powerful 911 GT2 RS

Innovative pistons created in a 3D printer have successfully completed their first endurance test in the engine of a 911 GT2 RS. Additive manufacturing processes (3D printing) enable the realisation of designs that are not feasible using conventional methods. It was therefore possible to optimise the piston structure to correspond to load conditions and also to integrate a cooling duct, while at the same time reducing each piston's weight by 10 per cent in comparison with a production forged piston. “This has allowed us to increase engine speed, lower the temperature load on the pistons and optimise combustion,” explains Frank Ickinger of Porsche's Advance Drive Development Department. “The result is more power and greater efficiency.” This means that a power increase of up to 30 PS is possible for the 515 kW (700 PS) Porsche 911 GT2 RS. The pistons have been developed as part of a cooperative project to develop an additive manufacturing process for highly-stressed drive components in which Porsche is working together with its supplier and development partner Mahle as well as the advanced technology company Trumpf. It has also been possible to include a further project partner in the form of the optical company Zeiss, which brings expertise in measurement and testing processes for additive manufacturing.

Optimised piston: lighter and with a higher load capacity thanks to its bionic design

The 911 GT2 RS is equipped with forged pistons as standard, but their potential for use in future high-performance engines is practically exhausted. Improvements have only been possible with changes that could no longer be realised using conventional production methods. In contrast, additive manufacturing makes it possible to implement a so-called bionic design in which material is only used in those locations where forces are transferred. For this topology optimisation, the engineers used a special design method that is matched to the specific conditions of 3D printing. Working with project partners Mahle and Trumpf, it has therefore been possible to reduce the weight of the pistons by 10 per cent and to validate the quality and performance capability of the topological structures with measurement technology from Zeiss. “We've always made sure that we always err on the safe side,” says Frank Ickinger. “Our simulations show that there is a potential weight saving of up to 20 per cent per piston.”

The second goal was the integration of an annular cooling duct behind the piston rings. This duct has a special cross-sectional shape and is closed like a tube apart from inlet and outlet openings for oil. Such a structure can be produced only by means of an additive manufacturing process. Thanks to this additional cooling, the temperature of the component has been reduced by more than 20 degrees in the piston ring area, which is subject to extreme thermal loads. The combination of all these measures makes for optimised combustion with higher pressures and temperatures, resulting in greater efficiency. “This is a good example of how the combustion engine still has future potential,” says Frank Ickinger.

Technology know-how from Mahle, 3D printing expertise from Trumpf, measurement and testing process from Zeiss

Porsche has relied on the competence of Mahle in the development of the 3D-printed pistons, just as it did for the production forged pistons in the 911 GT2 RS. The technology company has developed a weldable powder for additive manufacturing from their proprietary Mahle aluminium alloy M174+. The characteristic values of the printed material are comparable with those of the cast material for production pistons. In order to assess the suitability of the powder for the manufacturing process, it was subjected to multiple quality tests in cooperation with measurement technology specialists from Zeiss, including inspection by light microscope, scanning electron microscope and X-ray microscope.

The advanced technology company Trumpf was responsible for the development of the production process and printing. High-precision Trumpf TruPrint 3000 machines welded the powder layer by layer using the laser metal fusion process (LMF), also known as laser powder bed fusion (LPBF). In this process, the powder is fused by laser beam in a thickness in the µm range (0.02-0.1 millimetres), thus building up the piston layer by layer. The piston blanks are produced in this way with approximately 1,200 layers taking in the region of 12 hours. Testing using different non-destructive methods such as computer tomography, 3D scanning and microscopy, as well as analysis of dissected pistons, was undertaken with partners Mahle, Trumpf and Zeiss. These tests confirmed that the quality of the printed pistons did not differ from that of cast pistons.

Six pistons were then installed in a 911 GT2 RS engine for practical testing, which was subjected to a 200-hour endurance test on a test rig under the toughest of conditions. The test programme simulated 24 hours on a high-speed track, which included approximately 6,000 kilometres at an average speed of 250 km/h, including stops for refuelling. There were also 135 hours at full load and around 25 hours under drag load with different engine speeds in each case. The end result was that all pistons passed the test.

The development of piston production using additive manufacturing specifically for high-performance derivatives does not just show the opportunities available for exploiting previously unused potential, but can also offer enormous time savings in development. Due to the omission of the tool-making process necessary for cast pistons, it is therefore possible to reduce the procurement time for prototype pistons by over 30 per cent.

New possibilities, but also new design engineering requirements

3D printing opens up a host of new possibilities both for the optimisation of existing processes and also the development of future technology. “Things that have not been possible before can now be realised,” enthuses Frank Ickinger. This is also true for highly-stressed components, as is shown by the example of the 911 GT2 RS piston. Its lower weight and higher thermal resistance directly benefit the driver in that engine speed can be increased due to a reduction in oscillating masses. “An extra 300 rpm equates to around 30 PS more,” calculates Frank Ickinger. The torsional vibration damper can then be made smaller, thereby making the engine even more free-revving. Increased thermal resistance due to the lower temperature permits higher combustion pressures and even more advanced ignition timing – both factors that increase power and efficiency.

However, this extended design freedom does also go hand in hand with new design requirements, which include the engineers having to take into account the way that the components are produced layer by layer by fusion. “If there are overhangs with an angle of more than around 45 degrees, for example, it is necessary to incorporate support structures in order to stabilise the geometry and prevent distortion,” explains Frank Ickinger. “Otherwise, there is a risk of warping or bulging in an upward direction, which could damage the recoater used to apply the powder layer, with the result that the build process has to be aborted.” The goal is to generate as few supporting structures as possible because these usually have to be removed again later. Trumpf's expertise in the area of 3D printing has also made it possible to implement other design guidelines with respect to manufacturability and economic efficiency, such as minimising the number of support structures.

Working alongside Porsche development engineers, the design realisation of the optimised piston structure was tackled by the experts from Mahle. The technology group has been exploring the possibilities offered by additive manufacturing for many years already. Using CAD software, Mahle reproduced the structures that had been created as part of the topology optimisation. The innovative cooling duct was then defined, described by Frank Ickinger as “a perfect example of functional integration".

The design data was then subjected to a finite element simulation and analysed with respect to the resistance to failure, service life and temperature loading of the virtual piston. The additional annular cooling duct at the level of the piston rings proved to be particularly advantageous, causing a reduction in temperature by over 20 degrees in the area with the highest thermal load under the exhaust valves. The optimum design that satisfied all requirements was finally achieved after several design and calculation loops. On this basis, the engineers then created a production model and drawings for final machining.

Powder material developed from cast alloy

In parallel to the design engineering process, the experts from Mahle determined a suitable material. The cast alloy M174+ proved to offer the best prerequisites so the piston specialists developed the powder for the additive manufacturing process from this. In order to test its suitability for additive manufacturing, the powder was first analysed by Mahle and Trumpf by means of flowability and bulk density measurements as well as other measurements to determine the moisture content and grain size distribution. In order to detect pores in the powder grains, the experts examined the surfaces in metallographic sections. Gaseous contamination was determined by means of carrier hot gas extraction. In addition, the grain properties in relation to contamination, particle form, particle size distribution and gas inclusions were analysed by Zeiss's measurement technology experts by means of light microscopy, scanning electron microscopy and X-ray computer tomography. It was also important at this point to analyse the behaviour and structure of the powder with respect to multiple use, an important aspect for recycling and sustainability. The powder also did not show any changes relevant for the component properties in the case of multiple use. The goal was to be able to guarantee a homogeneous powder layer with reproducible powder characteristics in the subsequent build process.

For the first test specimens, Trumpf used additive manufacturing to produce simple geometric shapes such as cuboids and pins as material samples in order to determine the characteristics of the material. Several build jobs were performed in advance in order to find the optimum process parameters of the machine for this material. The results of the material characteristic analysis were consistently positive, the samples exhibiting largely uniformly distributed and round porosity with pore sizes between five and 50 µm. After the usual heat treatment, the test specimens' hardness was approximately the same as that of cast pistons. The physical characteristics were also similar to those of the cast material. Thermal expansion was slightly lower, for example, and the reversed bending fatigue strength values matched those of cast materials at 150 degrees Celsius and 300 degrees Celsius. The characteristics of the additively manufactured samples even exceeded those of conventionally cast material samples in some cases.

Additive manufacturing with Trumpf expertise

Design engineering and material development took place in close co-operation with the experts from Trumpf. The company – which, like Porsche and Mahle, has its home in the Stuttgart region – is a pioneer in the field of 3D printing with metal. Together with the Fraunhofer Institute for Laser Technology in Aachen, Trumpf has been conducting research in the area of laser metal fusion (LMF), also known as laser powder bed fusion, since 1999. Trumpf launched its first LMF machine on the market in 2004. The experts from the company were therefore predestined to develop the optimum parameters for printing the components.

Trumpf used a precision machine from its TruPrint 3000 series to manufacture the pistons. In the LMF process, the components are built up gradually in a powder bed. This takes place in the process chamber where the supply cylinder, build cylinder, and overflow cylinder are located next to one another in one axis. The process starts by the recoater shifting the powder from the supply container over the build cylinder, thus creating a powder layer. Excess powder lands in the overflow container. The laser beam then heats the powder surface corresponding to the part contour and melts it into a solid metal layer which is bonded with the already fused layers underneath. In the next step, the build cylinder is lowered and the recoater applies the next powder layer, a process that is repeated until the component has been completely generated. Finally, the powder that has not been fused is removed from the build cylinder in an unpacking station. This exposes the component and it can be removed from the substrate plate.

Tests confirm the uncompromising quality of the printed pistons

Building up parts layer by layer is the key to manufacturing shapes and structures that are not possible with conventional production methods such as casting or milling. “The piston from this co-operative project is an example of how we can create added value with 3D printing. The process permits the creation of parts with special properties and which are both lightweight and stable at the same time. Almost all industries can benefit from this. In addition to the automotive industry, Trumpf products are aimed above all at the aviation and aerospace, medical technology and energy sectors,” says Trumpf project manager Steffen Rübling. The TruPrint 3000 machine was ideal for production of the pistons thanks to its 30-centimetre-diameter cylindrical build area, which enable the production of five 104-mm diameter pistons simultaneously. The Trumpf experts were also able to show that productivity could be increased by a factor of up to three with the TruPrint 5000 system, which is equipped with three lasers.

The first samples of the high-performance pistons from the printer were analysed in detail. In addition to tests performed by Mahle and Trumpf, project partner Zeiss applied the same methods used for testing the first material samples: metallographic sections, light microscopy, X-ray spectroscopy and computer tomography. The scanned data of the piston blank were compared with the CAD data to determine whether the geometry had changed during the manufacturing process. The deviations were in the tolerance range of a cast piston and were therefore acceptable. Another important point was the interior of the cooling duct and whether there was still powder or welding residue present that could become detached during operation. This was also not the case due to the correspondingly adapted design. The high-resolution computer tomography inspection performed by Zeiss made it possible to search for defects such as small cracks or inclusions in advance so that the pistons could be released for further tests. Even small defects were marked by means of a special process known as the microdefect history so that these could be examined again non-destructively after the first tests, if necessary. In addition to examination of the metallographic sections, porosity and density were also determined for samples and cut-out sections of the piston using the buoyancy method, in which the lower the gas content, the lower the buoyancy force. With a density of over 99.5 per cent, the pistons had the same value as cast components. Machining of the pistons at Mahle also did not reveal any disadvantages compared with cast M174+ material. The first test was then started on a hydropulser at Mahle where the piston was supported at the piston pin bore and loaded until failure. The number of completed load cycles was above the required number, so the test was therefore passed. The second test performed was the so-called boss tear-off test. In this test, the force required to tear off the piston pin boss is determined and the force value was also found to be in the same range as for cast pistons. The practical load test in a 911 GT2 RS engine finally confirmed the uncompromising quality of the additively manufactured pistons – and their potential for increasing performance and efficiency.

Additively manufactured twin-jet nozzles with improved jet quality

In order to supply oil to both this annular duct and, as on the production piston, the piston crown, a further component was produced using the 3D printer, which was a twin-jet oil nozzle made of stainless steel. “Production using conventional technology would have become very complex due to the geometry,” explains Porsche engineer Marco Klampfl. Manufacturing such a twin-jet nozzle conventionally would have meant realising a complex brazed or milled design, which also could not have been used in the engine package.

For this reason, the engineers designed an S-shaped and forked oil guide which was manufactured additively from stainless steel powder. This component was brazed together with the tube support and check valve to produce a piston nozzle. “Concerns that the oil jet quality might suffer due to poorer surface properties in 3D printing were not confirmed,” says Marco Klampfl. “In fact, the opposite was true, and we were able to show in comparative measurements that the jet quality was actually improved by further functional integration.”

Wide spectrum of applications for 3D printing at Porsche

Additive manufacturing offers great potential for Porsche in the area of product and process innovation as well as for new fields of business. Lightweight construction and functional integration are examples of product innovation, while agile development and flexible production are benefits in the area of process innovation. New business fields include personalisation as well as new offerings for customers and spare parts. This manufacturing technology is technically and economically interesting for Porsche specifically for special and small production runs as well as for motor sport. Additive manufacturing processes are also ideal for physically producing structures that have been designed and optimised by means of artificial intelligence (AI).

Porsche already uses additive manufacturing processes in several areas and is actively engaged in their further development. For example, since May, a 3D-printed body form full bucket seat has been available for the 911 and 718 variants used in motor sport. Here, the central section of the seat, in other words the cushion and backrest surfaces, is partly produced by a 3D printer. Customers will be able to choose between three firmness levels (hard, medium or soft) for the comfort layer in the future. Porsche Classic also uses additive processes to reproduce plastic, steel and alloy parts that had ceased to be available. As an example, the release lever for the clutch of the Porsche 959 today comes as a spare part from a 3D printer. Around 20 reproduced parts for Porsche classic models are currently manufactured using additive processes. The quality requirements of the original production period apply to all parts as a minimum specification but the new parts normally meet even higher standards.

Porsche sees the overall success of the project as confirmation that it remains on the right track with regards to 3D printing. Due to the comparatively high costs per component, additive manufacturing is currently suitable only for parts required in small quantities where there would otherwise also be high tooling costs. Since Porsche frequently offers small series and special-edition models, “we are also considering producing pistons using the LMF process as standard for a complete special series of high-performance engines,” reveals Frank Ickinger. Because there still used to be question marks about additive manufacturing for highly-stressed drive components in particular, the development engineer adds: “From design to production and through to finish machining, there are a great many new parameters and influencing variables that do not exist with traditional methods of production. We are going to need to reliably master all of them in order to achieve uniform quality so there is still plenty of work to be done for a series production process in the automotive industry."

Many projects in development, part reproduction and performance enhancement
As part of the cooperation with Mahle and Trumpf, an additional charge-air cooler was produced as a further component. This was integrated into the air pipe connecting the turbocharger and charge-air cooler. Thanks to the possibilities offered by 3D printing, the charge-air cooler has a much larger surface area for heat transfer, which permits optimisation of the flow routing and cooling. The effect is that the intake air is cooler and the engine's power and efficiency are increased.

The potential benefits of additive manufacturing are also being investigated and assessed in the area of electric drives. "Using the example of a highly-integrated electric axle, we were able to also show the potential improvements not only in the product but also in its development process. By applying new design methods, it has been possible to double the rigidity of the drive and reduce its weight by around ten per cent. Thermal management was also significantly improved by the integration of a transmission heat exchanger while 12 components being built in allowed the omission of 30 screws, 12 seals and numerous other parts. This does not just create advantages in packaging, but also significantly reduces assembly work. "These measures made it possible to reduce the production time by almost 20 minutes," explains Falk Heilfort from the Advance Drive Development Department. In addition, the use of copper as a printing material results in interesting concepts that offer great potential for electric motors. The topic of cooling can also be taken to a new level for pulse-controlled inverters and motors.

"For us developers, 3D printing offers a host of other benefits," adds Frank Ickinger. Since new components can be manufactured without forming tools, this considerably shortens procurement times, and the time saved means that more variants can be tested. On balance, test parts can actually be less expensive because there are no tooling costs. Tools themselves can also be produced in an additive manufacturing process. As an example, an injection mould with integrated cooling allows the optimisation of the cycle times of conventional production methods. In addition to metal, 3D printing can also be used to print plastic parts and complex sand cores for casting processes such as for cylinder heads, crankcases and electric motor housings, making it possible to achieve significant benefits in the area of cooling.

However, in spite of the rapid further development of additive manufacturing processes, there are currently still major restrictions relating to them. Firstly, there are the costs, which remain economically justifiable only for smaller quantities, depending on the component in question. Secondly, the size of the component is a further limiting factor because it is not yet possible to manufacture larger parts in the process chamber of printers currently available. In addition, it is necessary to extend the range of materials both for plastics and metals. Finally, additive manufacturing still has to qualify itself for (small) series production processes in the automotive industry in terms of quality and reproducibility as well as economic efficiency.

“However, I am certain that additive manufacturing will be an established part of automotive development and production in 10 years' time at the latest,” says Frank Ickinger.

Image material available in the Porsche Newsroom (newsroom.porsche.com) and the Porsche media database (presse.porsche.de).