INNOVATIVE COMPONENT TEST CONCEPT FOR CRANKSHAFTS

The crankshaft is a core component of today's internal combustion engines and during operation is subject to complex mechanical loading. The transition radii of the crankpins to the crankwebs and the outlets of the oil ducts for lubricating the crankshaft journals and pins are the points that are susceptible to fatigue fractures. For this reason, expensive surface strengthening measures are integrated in the production process. IABG has developed a new test concept for crankshafts to examine the effectiveness of these measures in a fatigue strength test under loading conditions that are as realistic as possible.

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COMPONENT TESTING MUST BE REALISTIC

To evaluate the fatigue strength behaviour of components, it is necessary to have tests which load the points that are susceptible to fatigue fractures in as realistic a manner as possible. If a component has multiple critical zones, but each with a different load level, then the test concept must also ensure that the load levels of the individual zones are reproduced as realistically as possible. This requirement for equivalent damage testing of components is one of the most important criteria for comparing different test methods.

On crankshafts, these zones that are susceptible to fatigue fractures can be both at the transition points (fillets) of the crankwebs to the crankshaft journals and pins and at the oil duct inlets and outlets of those crankpins. To increase the local fatigue strength in these zones, more mechanical and/or thermal surface strengthening measures are implemented in the production processes, which is time-consuming and expensive. In the case of crankshafts, equivalent damage testing is a critical requirement for deciding whether individual process steps can be left out or substituted with less expensive measures that provide less fatigue strengthening.

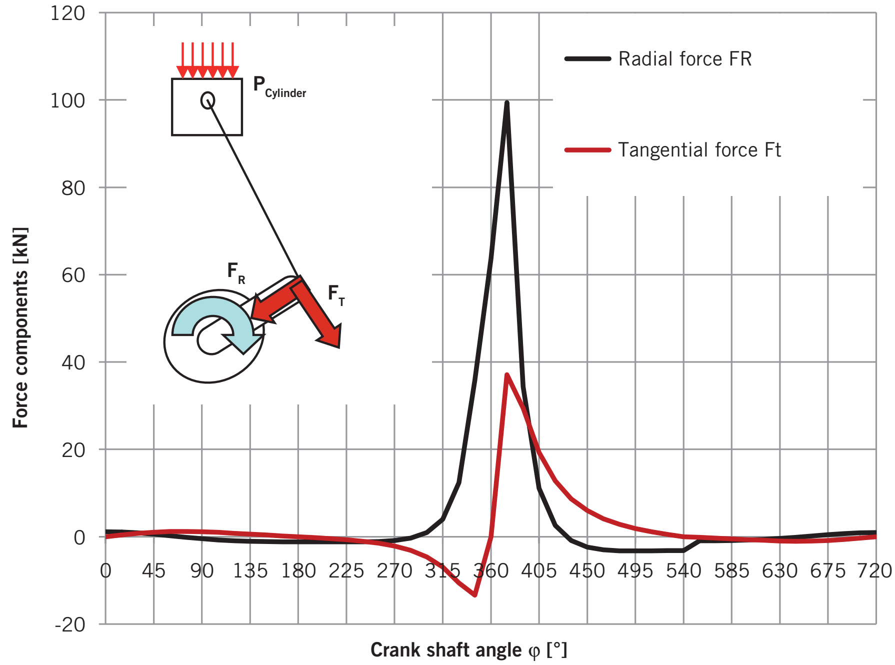
CRANKSHAFT LOAD SITUATION

During operation, crankshafts are subject to complex, time-variable loading. To examine this more closely, observations are focused first on the external force excitation due to the cyclic gas forces in the individual cylinders and the resulting loading of the separate crankshaft zones. The crankshaft of a four-cylinder engine in series production is used as a typical model for this.

Due to the thermodynamic working process, the time-variable cylinder pressure exerts a corresponding cyclic radial and tangential force on the individual crankshaft pins, ❶. Whereas the radial force is supported by the two adjacent cylinders, the torsional moment caused by the tangential force is transmitted to the output end of the crankshaft. Thus the torsional moment caused by the tangential force at the crankshaft pin of cylinder 2 also loads in full force the crankshaft journals of the following cylinders 3 and 4. However, the crankshaft journals 1 and 2 of cylinder 1 are not subject to any torsional load due to the combustion process in cylinder 2. Each crankshaft journal thus experiences a different number of torsional-moment stress cycles during the service life of an engine, ❷. Therefore, an equivalent damage testing concept should take this circumstance into account.

The crankshaft is statically over-defined due to the multiple bearing of the crankshaft journals. This over-defined bearing permits deformation of the crankshaft under the loads exerted only within the ranges of bearing clearance and stiffness of the bearing support. This prevents the crankshaft journals from being twisted or offset perpendicular to the axis of rotation when the crankshaft is subjected to torsional loading. This means that no actual torsional load is exerted on the crankshaft pins. The torsional moment in the crankshaft journals is transformed by the crankwebs into a shearing and bending load on the crankshaft pin. A torsional moment only occurs again in the successive crankshaft journal.

The radial force essentially leads to a bending load in the crankshaft section in which the ignition occurs. ❸ shows the main types of load exerted on the separate crankshaft sections. A distinction is made between crankshaft pins, crankshaft journals and crankwebs. With the engine ignited, loads in addition to those discussed here are exerted by the dynamic gas forces. These are a result of the drive shaft dynamics and the superimposed inertia forces. In most test concepts, these can be taken into account by increasing the load or by changing the level of the mean test load at least for the examined zones susceptible to fatigue fractures.



❶ Schematic force component characteristic of a crankpin

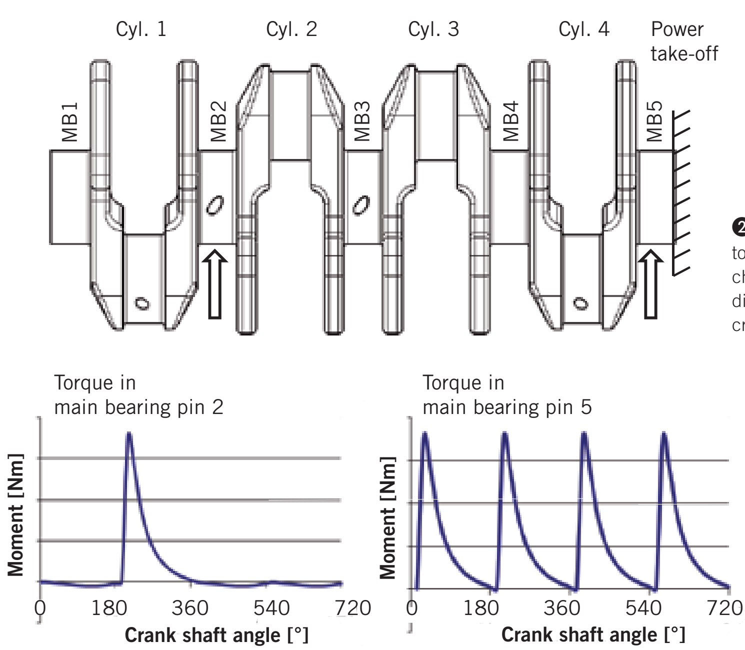
COMMON METHODS FOR TESTING CRANKSHAFTS

The pure bending test and the pure torsion test are the two common test methods for the experimental fatigue analysis of crankshafts.

In the bending test, individual crankshaft segments are tested by applying an invariable cyclic bending moment (usually variable or fluctuating) over the segment. As the following computational comparison of different test concepts demonstrates, it is mainly the fillet zones of the crankshaft journals and pins that are loaded.

In the torsion test, the complete crankshaft is frequently tested with a varying moment of torsion from shaft end to shaft end. In this case, the crankshaft is not usually supported on the crankshaft journals so that the component can freely twist. As a result, the torsional moment is applied over the complete length of the crankshaft and thus also to the crankshaft pins. In this test method, therefore, mainly the oil duct inlets and outlets are loaded and examined.

Since both test methods examine different points that are susceptible to fatigue fractures, usually both have to be employed for experimental fatigue analysis of the complete crankshaft. Due to the unreal bearing situation, the deformation picture and thus the local loads reflect reality only in a very restricted way. The different weighting of the fillet and oil duct outlets in the bending and torsion tests makes it difficult to draw a relationship between the two sets of test results and to the real implementation in an ignited engine.



❷ Schematic torsional moment characteristics in different main crankpin bearings

NEW CRANKSHAFT TEST CONCEPT FOR OPERATIONALLY REALISTIC FATIGUE ANALYSIS

As explained in the previous sections, there is no torsional loading of the crankshaft pin areas of a crankshaft, but rather a superimposed shearing and bending load. IABG has developed a new crankshaft test concept to reproduce this type of load in testing and replace the two separate test methods by a combined test. It provides multiple bearing with real bearing play in all main bearing blocks as well as torque-proof mounting of the output end of the crankshaft, ❹. Force is transmitted via a so-called connecting-rod dummy, ④, directly on the crankpin, whereby the force is applied at a variable angle to each crankweb position. The test force is thus divided into radial and tangential force components and so reproduces the conditions in an ignited engine. The tangential force component causes torsional load on the crankshaft journals at the output end and is supported by the torque-proof mounting of the output end.

This transmission of test force and the bearing of the crankshaft at all crankshaft journals cause comparable local load conditions to be applied both in the crank throw currently being tested and in the zones at the output end. The torsional load from the tangential force is thus reproduced realistically.

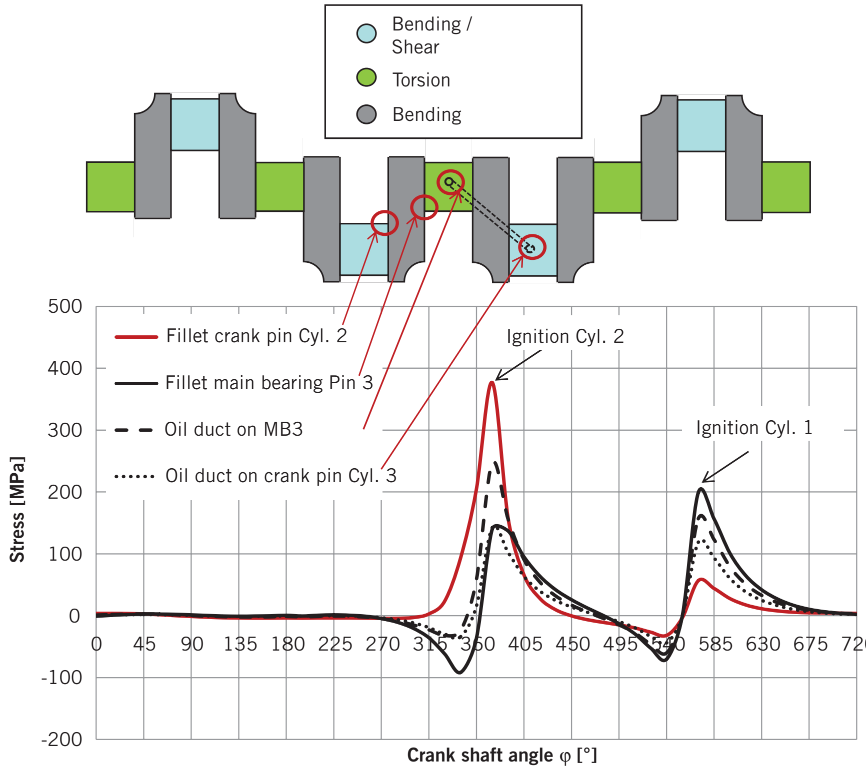
TEST PERFORMANCE AND EVALUATION

The test sequence for the individual crank throws prescribes that testing begins with the crank throw opposite to the output end. The force is to be applied by a servo-hydraulic system or a resonance force generator. Each crank throw is tested until a definable abort criterion is reached. Testing then continues with the adjacent output end crank throw. The experimental fatigue analysis is performed in this way for all the crank throws. Since a fatigue fracture might be caused by the test force applied to the crank throw being tested, the other crank throws remain intact and are able to be used for the successive tests. However, through the correct reproduction of the tangential force flow over the output end zones of the crankshaft, the loads and possible predamaging also occur "realistically" in the segments not subjected to the connecting-rod force.

The test program provides for the testing of an appropriate number of crankshafts. The number of test results produced for each crankshaft corresponds to the number of crank throws in each case. These results can be evaluated both as a whole and individually for each crank throw. The influence of load on adjacent crank throws on fatigue and service life can therefore be examined and evaluated specifically for each crank throw.

COMPARISON OF DIFFERENT TEST CONCEPTS

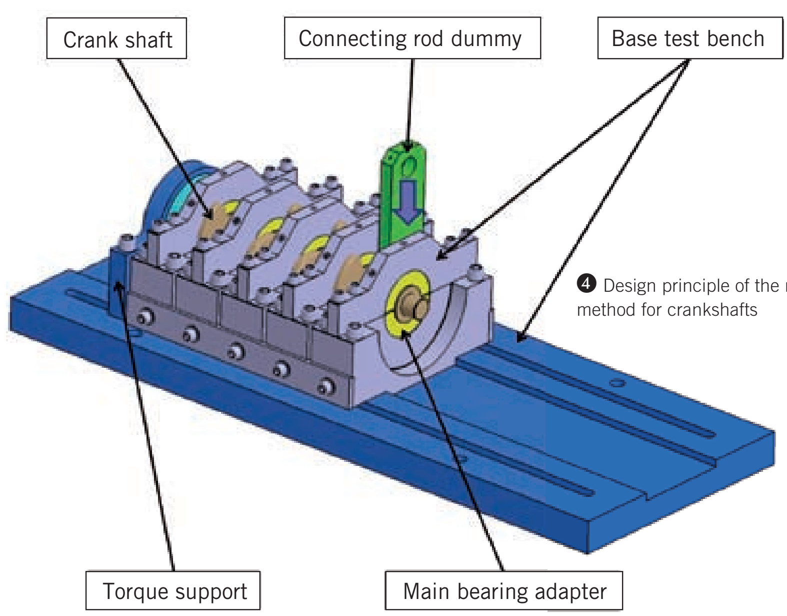
To be able to compare different test concepts, an FE analysis is used to determine the local loads on a generic crankshaft of a four-cylinder engine for the following three test procedures:



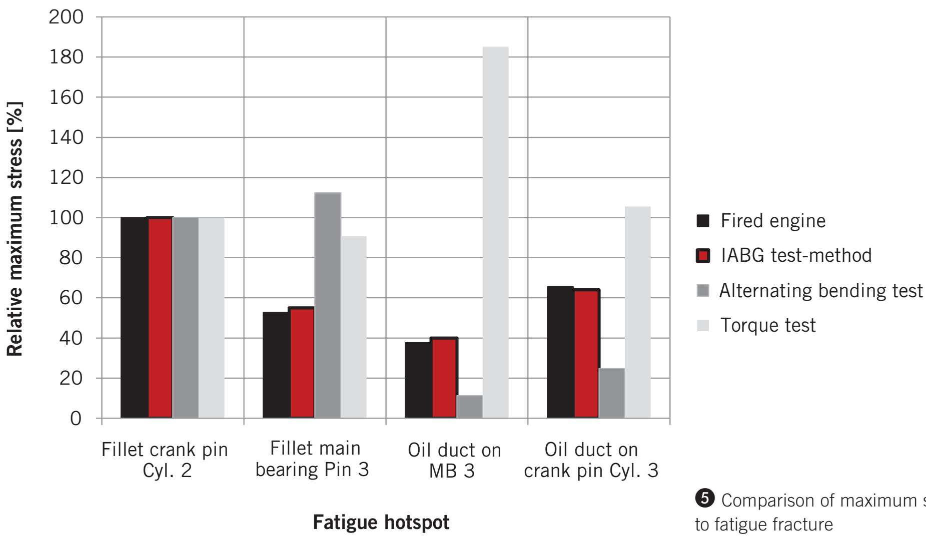
❸ Main types of load on the separate crankshaft segments (top) and simulated loading of the four examined zones susceptible to fatigue fractures in an ignited engine (bottom)

: bending test
: torsion test
: IABG test procedure with combined load and realistic bearing.

The local loads resulting from the calculations are compared with those from an ignited engine. For this, gas excitation forces corresponding to the ignition sequence are applied transiently to each crankpin. Additional dynamic effects and inertia forces are not taken into account here. The resulting additional loads can be taken into account by changing the test load curve accordingly.



❹ Design principle of the new test method for crankshafts



❺ Comparison of maximum stresses at different points susceptible to fatigue fracture

By way of example, a comparison will be made of the loads at the following points on a crankshaft which are typically susceptible to fatigue fractures:

: fillet on the crankpin of cylinder 2
: fillet on the crankshaft journal HL3
: oil duct on the crankshaft journal HL3
: oil duct on the crankpin of cylinder 3.

The simulation of the ignited engine over two rotations of the crankshaft in ③ (bottom) shows that based on the present assumptions the maximum load occurs at the fillet of the crankpin of the second cylinder. The second highest maximum stress is observed at the oil duct outlet on the crankshaft pin of the third cylinder. This is approximately 66 % of the stress in the fillet. Both stress peaks occur approximately at the time of ignition in the second cylinder. As can be seen in the diagram in ③, the ignition in cylinder 1 also causes stress peaks. Here, the fillet of the crankshaft journal 3 is subjected to its highest load.

Now, to compare the three different test methods with the ignited engine characteristics, the maximum stresses calculated in the four examined zones susceptible to fatigue fractures are evaluated and referenced to the maximum stress at the fillet of the second cylinder's crankpin, ❺. The comparison clearly shows that with the pure bending test with alternating loads, the load on the fillet on crankshaft journal 3 is significantly higher than with the ignited engine, whereas the load at the two oil duct inlets and outlets is too low. In the case of a fluctuating bending load, the highest stressed region would be crankshaft pin of cylinder 2 as in the fired engine, while the oil ducts would remain at a level that is significantly too low.

The torsion test shows a clear excess of stresses at the two oil ducts, but the stress at the fillet on crankshaft pin HL3 is too low compared with the fillet on the crankshaft journal. This is based on a fluctuating torsional load. In the case of a torsion test with alternating load, the significant excess at the oil duct points would not decrease. Hence, also with the pure torsion test of the complete crankshaft, the maximum stresses are not equivalent to the ones in the fired engine.

Neither one of the classic methods alone nor a combination of both methods is capable of adequately reproducing the loads in an ignited engine. If the loading on the fillet of the second cylinder is to be analysed, much higher loads must be applied to other points than in the ignited engine. This may cause fatigue damage during testing in these regions, which may have no relevance for the fired engine due to over stressing caused by the testing concept. This may lead to oversizing or process steps for increasing fatigue strength that are not necessary in practice, or to insufficient testing of the fillet of the second cylinder.

The new IABG test concept demonstrates a very good match of loads with those of the ignited engine at the points of a crankshaft susceptible to fatigue fractures. All the points examined can be tested realistically at the same time in one test run. Both the geometric design and the implementation of measures to increase fatigue strength can thus be oriented on the realistic conditions in an ignited engine. The proposed test method can therefore contribute significantly towards avoiding oversizing, eliminating expensive production process steps and providing reliable fatigue analyses for crankshafts.

SUMMARY

This document presents a new test concept for the experimental fatigue analysis of crankshafts. The test force is applied directly to each crankshaft pin in a similar manner as in a real ignited engine. The resulting radial and tangential forces provide very realistic loading of the zones susceptible to fatigue fracture. A computational comparison between the ignited engine, the two common bending and torsion test methods and the new IABG test method reveals significant advantages. The standard fatigue analysis of crankshafts to date based on the two separate test methods can be readily replaced by the new IABG test method which provides a very realistic reproduction of the local loads. In this way, the potential of lightweight construction can be better exploited, allowing a better evaluation of potential cost-reducing measures in the production of crankshafts.

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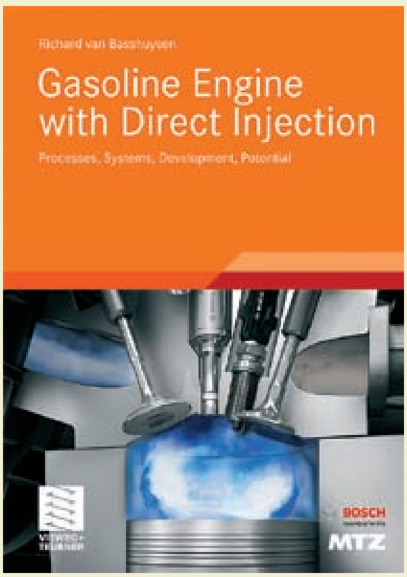

Richard van Basshuysen

Gasoline Engine with Direct Injection

Processes, Systems, Development, Potential

2009. xviii, 437 pp. With 399 Fig. Hardc. EUR 49,00
ISBN 978-3-8348-0670-3

Direct injection spark-ignition engines are becoming increasingly important, and their potential is still to be fully exploited. Increased power and torque coupled with further reductions in fuel consumption and emissions will be the clear trend for future developments. From today's perspective, the key technologies driving this development will be new fuel injection and combustion processes. The book presents the latest developments, illustrates and evaluates engine concepts such as downsizing and describes the requirements that have to be met by materials and operating fluids. The outlook at the end of the book discusses whether future spark-ignition engines will achieve the same level as diesel engines.

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Dr.-Ing. E. h. Richard van Basshuysen was Head of Development for premium class vehicles and for engine and transmission development at Audi. Today, he is editor of the magazines ATZ and MTZ. The editor was supported by a distinguished team of authors consisting of 22 experts and scientists from industry and universities.

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Gasoline Engine with Direct Injection
ISBN 978-3-8348-0670-3
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