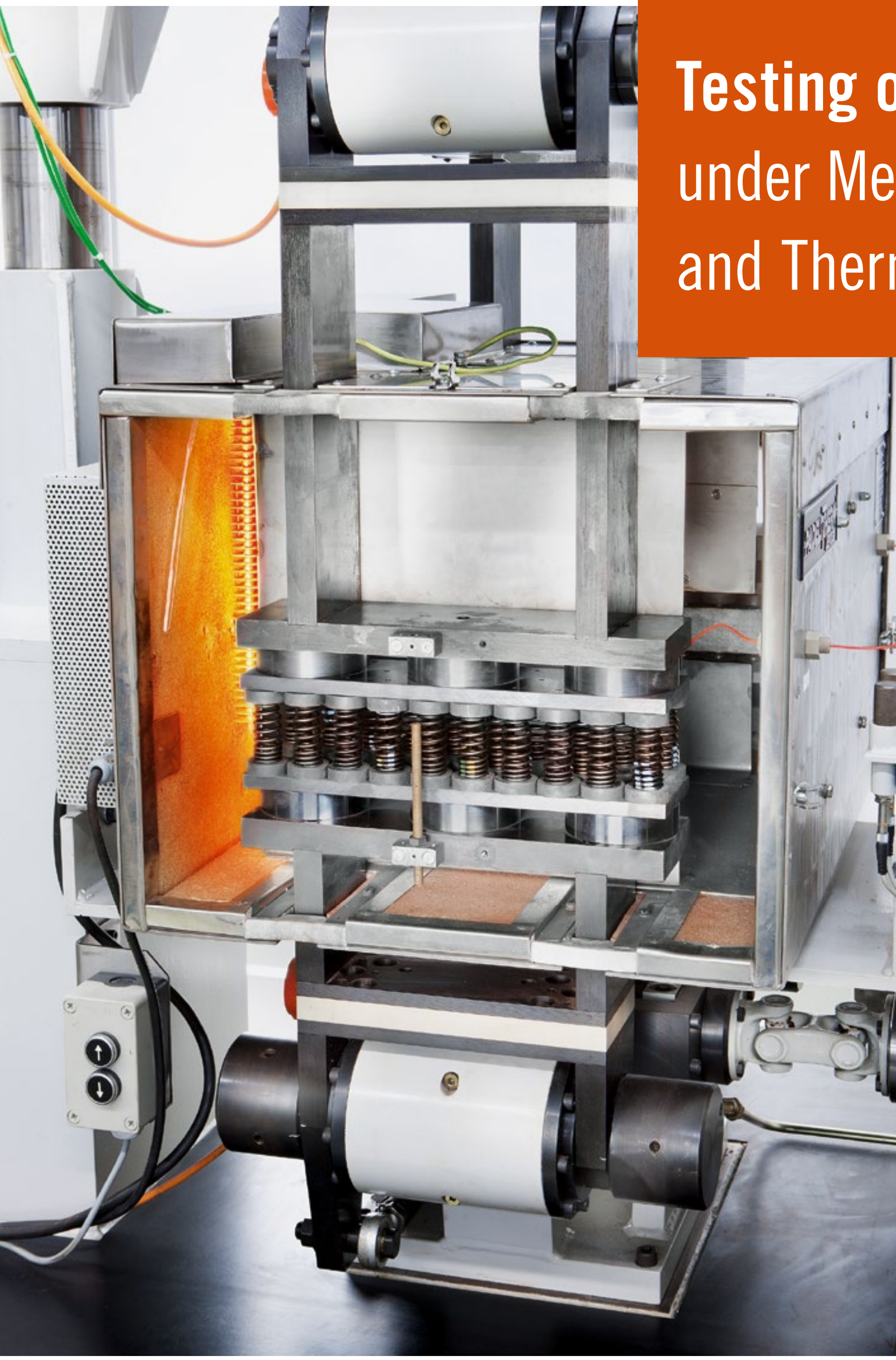

Testing of Valve Springs under Mechanical and Thermal Loads

The failure of valve springs can result in damage to the whole engine. A new testing procedure developed by IABG provides experimental verification of the fatigue strength of valve springs with very good statistical validation. In order to achieve a sufficiently high number of test results, a specially developed resonance testing machine is used.

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TESTS UNDER REALISTIC CONDITIONS

While valve springs may cost very little in comparison to the engine as a whole, their fail-safe stability is no less significant for a vehicle's reliable performance. Valve spring failure can cause major damage to the entire engine and should therefore be ruled out with utmost efficiency, i.e. by means of reliable design and validation concepts for valve spring, engine and vehicle manufacturers. Comparative tests to evaluate the endurance limits of valve springs should be conducted under realistic conditions. Testing the fatigue behaviour of valve springs in the cylinder head during fired operation and at elevated temperatures produces results close to reality. The test setup is very complex, however, and the test parameters, particularly the load amplitude, can only be influenced to a certain extent. The reliable validation of the fatigue behaviour of valve springs requires a large number of springs to be tested under variable, freely selectable loads – ideally to the point of fracture. For this purpose, IABG has developed a testing procedure in compliance with the requirements of vehicle and spring manufacturers as well as containing the testing technology necessary to determine the fatigue strength limits of valve springs at elevated temperatures and high test frequencies.

VALVE SPRING STRESS

A valve spring in an assembly forms an oscillatory system with several degrees of freedom that is actuated by the camshaft. During valve timing, valve lift actuation results in a phased semi-sinusoidal signal sequence, respectively interrupted by phases in which the valve is closed. Due to the deviations from a periodic sine wave, this actuation contains components of frequencies significantly higher than the camshaft's rotation frequency. The wide frequency spectrum enables the actuation of superimposed longitudinal or lateral vibrations within the valve spring that occur simultaneously with the valve opening movement and that lead to local stress that can be much higher than that of the quasi-static deformation caused by the valve stroke.

FIGURE 1 shows the typical frequency response of a valve spring in the cylinder head, depicting the envelope of the local shear stress over time across the engine speed. At about n = 1800 rpm, the valve spring deforms more or less exactly according to the cam stroke. Higher engine speed causes superimposed longitudinal oscillations that lead to a significant increase of the local strains within the spring. The local deformation limit is reached when two spring coils touch each other (block). The downward stress is limited by a configuration that prevents valve bouncing and/or full valve spring relaxation. The envelope maxima and minima usually occur at different engine speeds. Under real-life operating conditions, the valve spring would run through these different frequency ranges briefly and would therefore need a very long time to reach the fracture-relevant number of peak-stress cycles between the absolute minimum and the absolute maximum.

During engine operation, the superimposed longitudinal vibrations can lead to two neighbouring spring coils touching each other, while the respective adjacent coils are spaced apart from one another. Despite the low spring compression, the oscillation state depicted in the centre of **FIGURE 2** causes the maximum possible shear stress τ_{max} on the inner side of the spring.

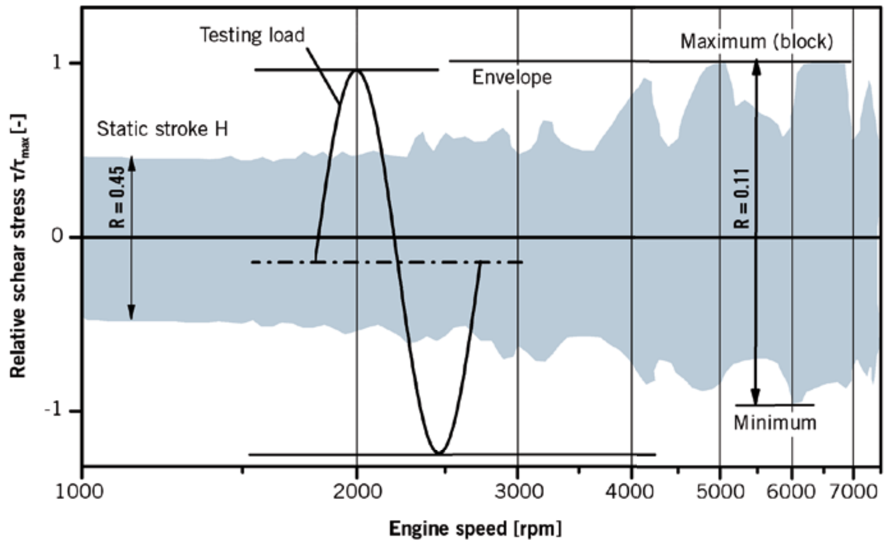

FIGURE 1 Typical frequency characteristics of a valve spring [1]

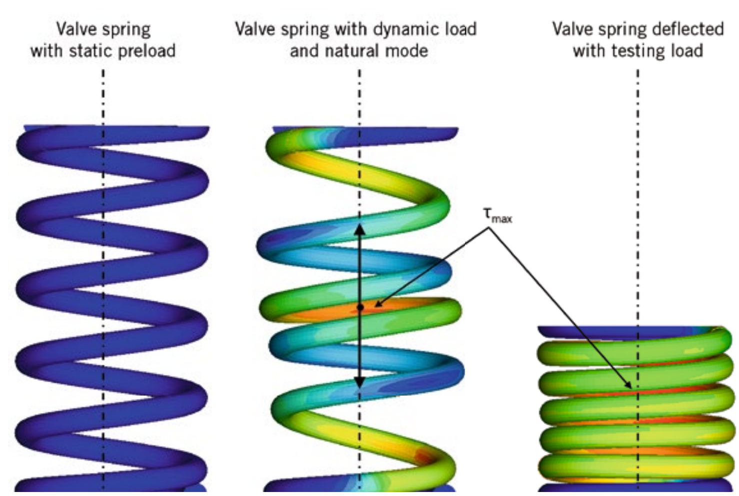

FIGURE 2 Engine and test bench load situation of a valve spring (low strain in blue, high strain in red)

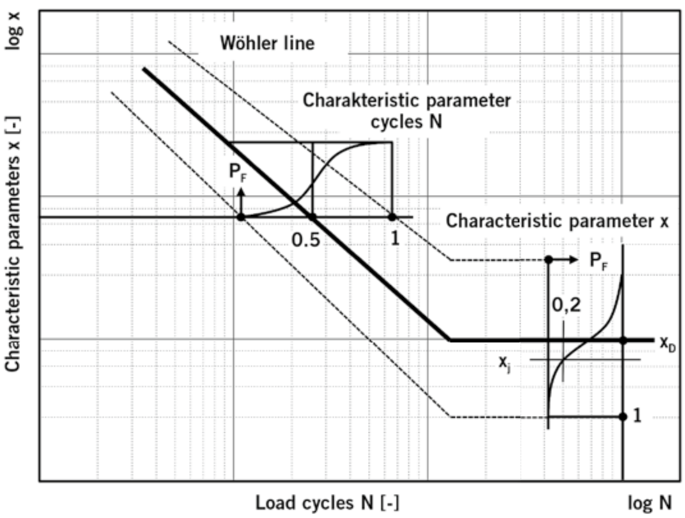

FIGURE 3 Probability of failure P_F within time and endurance limit range (schematically)

TESTING STRATEGY

To develop fatigue-resistant valve springs, manufacturers need to be aware of the failure rate of springs across the endurance range of the Wöhler fatigue curve, **FIGURE 3**. A large number of test results including both fractured items and test items without fracture is necessary to validate the extrapolation for low probabilities of failure for large component quantities [2].

Because the valve spring rarely passes through the different relevant frequency ranges for maximum and minimum local strains during operation and therefore only very gradually reaches the fracture-relevant number of peak-stress cycles, it makes no sense to simulate the real valve lift stress over time. The objective of a test must be to reach the maximum possible strain amplitude in each relevant spring coil as often as possible in order to create a sufficient number of fractures with the resulting, time-scaled maximum load. Since the valve spring is actuated by the camshaft within a wide frequency spectrum, the achieved test frequency is irrelevant in terms of fatigue strength [3] as long as it is guaranteed that the maximum spring stress is achieved. For efficient testing purposes, the tests should be conducted at elevated temperatures with the maximum possible spring deformation almost to the point of “block” as well as with the highest possible test frequency, **FIGURE 1**, **FIGURE 2**. Many springs as possible are tested in a specific testing plan, so the results can be analysed using the probit model to provide the best possible statistical validation for each load level. The test results are then evaluated against the logit distribution.

PROBIT METHOD AND DISTRIBUTION FUNCTION

The probit method is used for the statistical evaluation of test results with and without failure within the endurance range of a Wöhler fatigue curve. This method delivers an estimate of the probability of failure P_F within the endurance

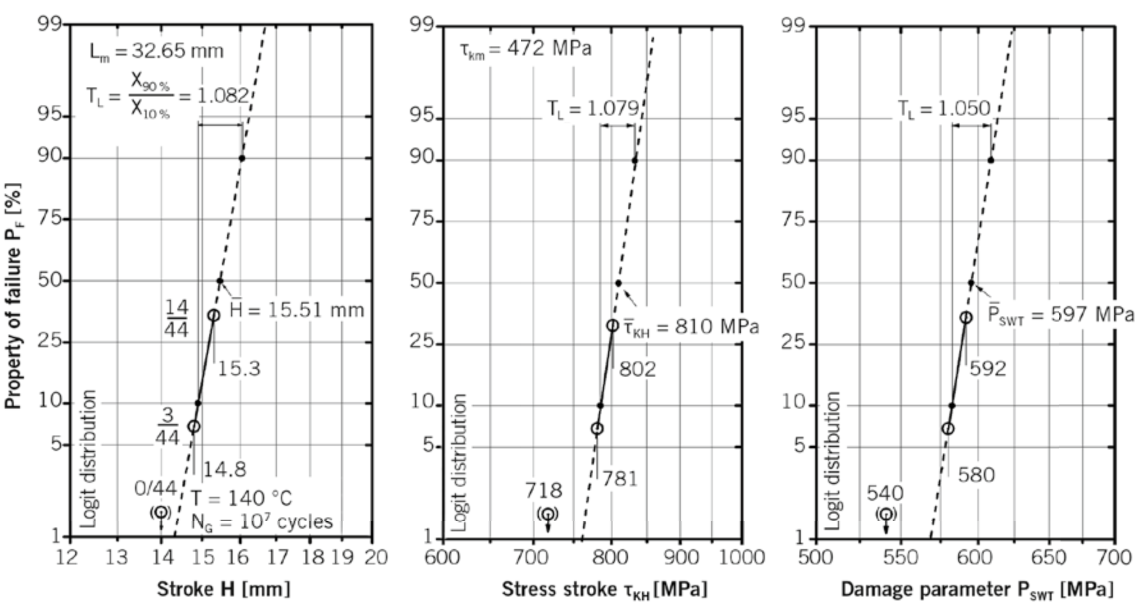

FIGURE 4 Data analysis in the probability net [6]

range as depicted in **FIGURE 3**. The probability for the number of fractures in a random sample being tested at a defined strain level can be determined statistically and depicted in a probability diagram [4].

During a test run, springs are examined for at least two load levels with an identical mean load. The evaluated test configurations for a spring type can be depicted against the range of the stroke H in a probability net, **FIGURE 4**.

Different spring types can be compared by plotting the probabilities of failure across the maximum shear stress τ_{KH} amplitude. If additional test results with differing mean stresses are to be compared, it makes sense to plot the probability of failure against the Smith-Watson-Topper fatigue damage parameter P_{SWT} which is very useful to describe the mean stress sensitivity of high-tensile spring steels [5]. Comprehensive studies at IABG have shown that the logit distribution is an excellent method to describe results of fatigue tests for valve springs [1], which is why it is used to scale the probability axis. The regression line derived from the results reflects the mean value and the scatter of an individual property. These two parameters combined with the applied distribution function provide an extremely compact description of the test results and can be used for an easy comparison with other results.

FATIGUE STRENGTH ANALYSIS

IABG has conducted comprehensive tests to determine the fatigue endurance limit of valve springs at elevated temperatures and has evaluated the results statistically [6, 7, 8]. **FIGURE 5** shows IABG's test results in a probability net for the logit distribution, evaluated against the fatigue damage parameter P_{SWT}. The test configurations depicted in this probability net are results derived from tests on valve springs from varying steel, wire and spring manufacturers and provide an overview of achievable fatigue strength and scatter. The varying sizes of the points displayed illustrate their respective weighting based on the number of tests and the resulting fractures.

The scatter represented by the regression line in the chart is significant as regards the assessment of a material in terms of its fatigue strength limit. During the test series conducted at IABG, the best valve springs achieved a variance of $T_{L,90/10} \leq 1.08$ for the fatigue damage parameter P_{SWT}. The fatigue damage parameter P_{SWT} is a measure for the influence of the local stress amplitudes and mean values on the damage regarding variable mean loads. In order to minimise the failure rate in a large quantity of valve springs, a low scatter is essential and more important than a high tolerable stress level with a probability of failure of $P_F = 50$ % [6].

The primary objective should therefore be to minimise the scatter of the fatigue limit because it has a stronger impact on the load capacity proven with a very low probability of failure than the mean value of the fatigue limit. The regression line on the right in **FIGURE 5** represents the highest level of all fatigue strength values determined in the valve spring tests. This upper limit is considered state of the art and currently represents the maximum achievable component quality. The fatigue strength and scatter determined in this test series can therefore be used as a guideline for a quality standard for other valve spring types.

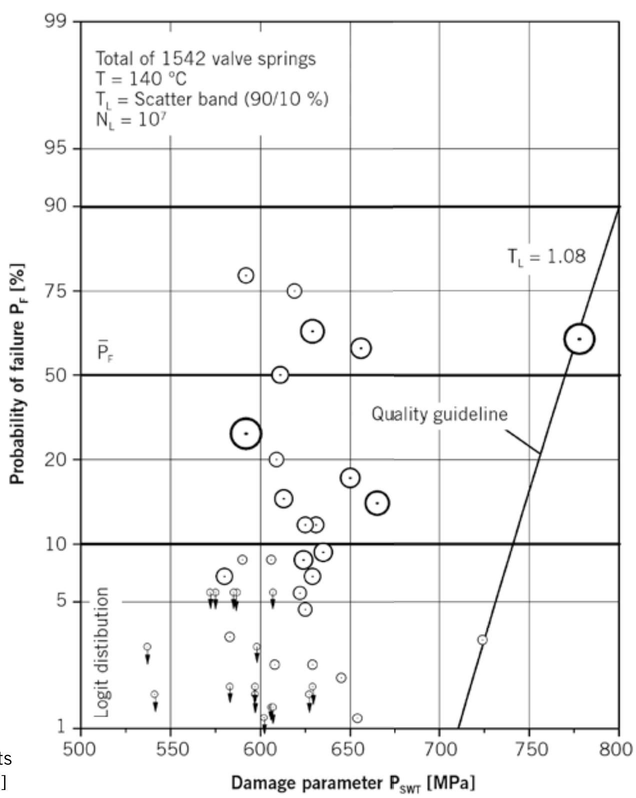

FIGURE 5 Overview of the fatigue strength test results derived at IABG [7]

IABG VALVE SPRING TESTING FACILITY

IABG has developed a resonance test bench to meet all requirements necessary to test the fatigue strength of valve springs. Between two rocker arms a large number of test items can be mounted simultaneously, **FIGURE 6**. The upper rocker arm is lowered to preload the springs to the desired initial mean load. Together with the test items, they form a spring mass system with a characteristic eigenfrequency. With this eigenfrequency, a natural oscillation can be excited and maintained with very little energy input. The vibration is actuated at the lower arm and can be adjusted to the desired frequency and amplitude. The resonance frequency of the oscillatory system used as test frequency depends on the spring rate, the number of test items and the vibrating masses and can be set within certain limits by adjusting these parameters.

The fixture plates can be used to test up to 96 springs simultaneously, depending on their size and spring rate. When a spring is failed, the stiffness of the oscillatory system changes and the test bench stops operating due to the changing of the resonance frequency. Additionally, the test bench allows elevated tempera-

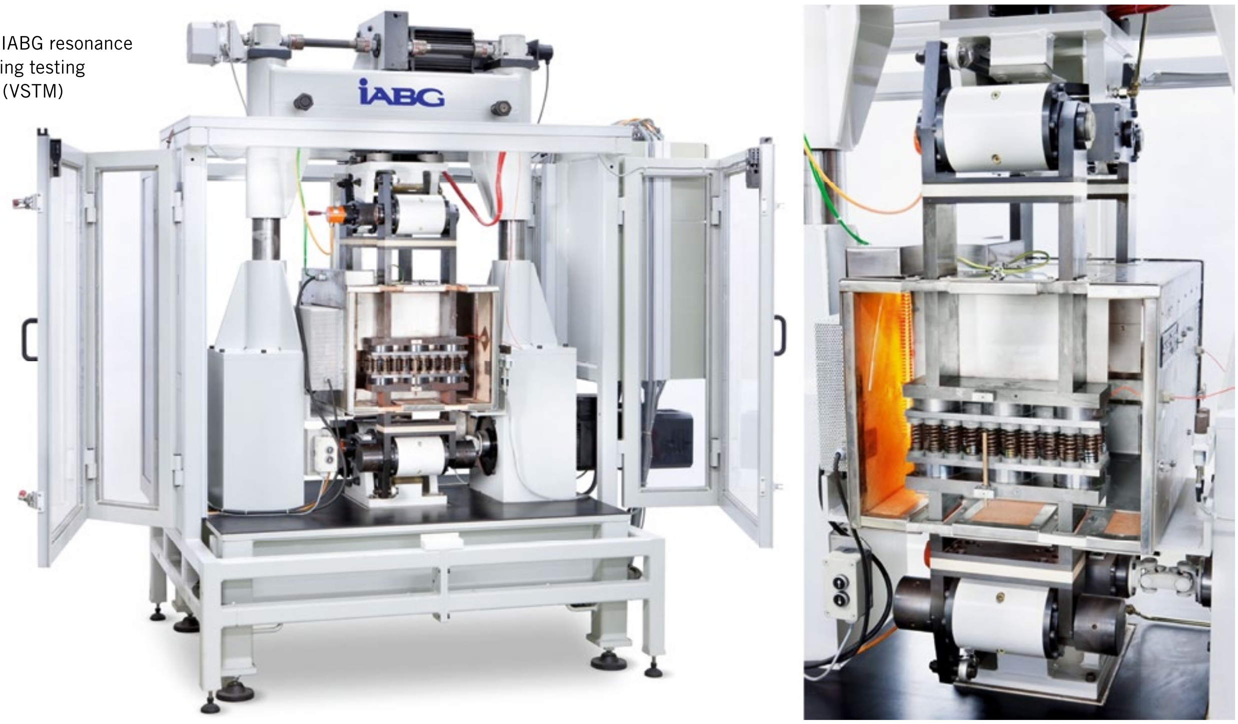

FIGURE 6 IABG resonance valve spring testing machine (VSTM)

tures of up to 200 °C and can be used to examine thermal influences on the fatigue strength and setting behaviour of valve springs. Because of the full mass balancing the test bench can be installed without a complex vibration-insulating sprung foundation.

SUMMARY AND OUTLOOK

Valve springs are safety-critical components and indispensable for the reliable operation of an engine. As the failure of just one of these components can affect the performance of the entire engine, a very low probability of failure is desired and must be proven by fatigue tests and corresponding statistical validation. A valve spring in an assembly forms an oscillatory system that is actuated by the camshaft. Besides the frequency of the cam drive, the actuation contains significantly higher frequencies that can excite lateral oscillations that stress the spring locally up to the point of block. Realistic tests in a fired engine make little sense because, despite the immense effort, the damaging stress cycles caused by very high stroke levels rarely occur, since absolute maximum and minimum values occur at different engine speeds. It is therefore not possible to achieve a sufficient number of stress cycles with the maximum cyclic range. This is why tests should be carried out at high frequency, the maximum possible cyclic stroke and at an elevated temperature. The suggested probit method provides experimental proof of fatigue strength and excellent statistical validation. To achieve the necessary volume of test results, IABG produces and uses resonance test benches that allow an energy-efficient and time-saving testing of large quantities of springs at elevated temperatures. The suggested method has been used to achieve comprehensive test results for valve springs by different manufacturers and to quantify the relevant influencing factors. IABG conducted a qualitative analysis of the impact of temperature as the most important influencing factor for a spring's fatigue strength and dynamic setting behaviour. A quality standard was defined based on the extensive test series. This standard can be used to measure the quality of future valve spring generations.

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