# Current developments in the experimental durability evaluation of coated coil springs under realistic loading

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**ABSTRACT**

Within a comprehensive test campaign different spring manufacturing technologies and surface protection systems were investigated comparatively regarding the fatigue lifetime. With the selected experimental procedure the relevant operating loads like deflection, abrasion, grit impact and corrosion were considered. As a result a significant reduction of the fatigue strength can be determined by means of mechanical damage of the spring surface and subsequent corrosion. The production technologies applied by the spring manufacturers cannot help to improve the fatigue lifetime. Only the application of a modified coating could prevent such a big lifetime reduction due to mechanical damage and corrosion. Merely on the basis of these measures the full potential of the spring technologies regarding lightweight design can be exploited completely.

**KEYWORDS**

Suspension spring, corrosion, grit impact, coating, resonance tester

## 1. INTRODUCTION

The durability of vehicle springs is subject to numerous influencing factors. Besides the mechanical stress resulting from axle kinematics, mounting and application profile, a spring's fatigue life mainly depends on material, manufacturing and environmental conditions. Vehicle springs are made of (ultra) high-tensile and heat-treated steel, subjected to high static and cyclical loads and sensitive to superficial defects that can be caused by mechanical and corrosive action during production or operation. To reduce the risk of fracture, manufacturers use different types of surface coatings that provide protection against both corrosion and mechanical damage by grit or other abrasives.

This document examines the complex stress conditions for vehicle springs and describes the most frequent types of damage. It presents the findings of an extensive test project that was conducted primarily to examine the influence of corrosion combined with mechanically generated surface defects on the durability of vehicle springs. In the course of this project, different spring production technologies and surface coating systems were compared for a generic spring type in order to determine the best manufacturing and corrosion protection practices that would ensure a long fatigue life as well as to derive the necessary measurements and parameters for reliable testing.

This comprehensive testing programme involved several vehicle and spring manufacturers. The following pages provide a first-time qualitative evaluation of the results.

## 2. OPERATIONAL LOADING

Chassis springs are installed between the upper and lower spring plate and pre-tensioned by the weight of the vehicle throughout the entire period of use. The static pre-load arises from the initial tension generated during installation and the total vehicle weight that depends on the vehicle payload. Under operating conditions, the spring is additionally subjected to loadings with variable amplitudes. The maximum and minimum deflection depends on the axle kinematics (Figure 1).

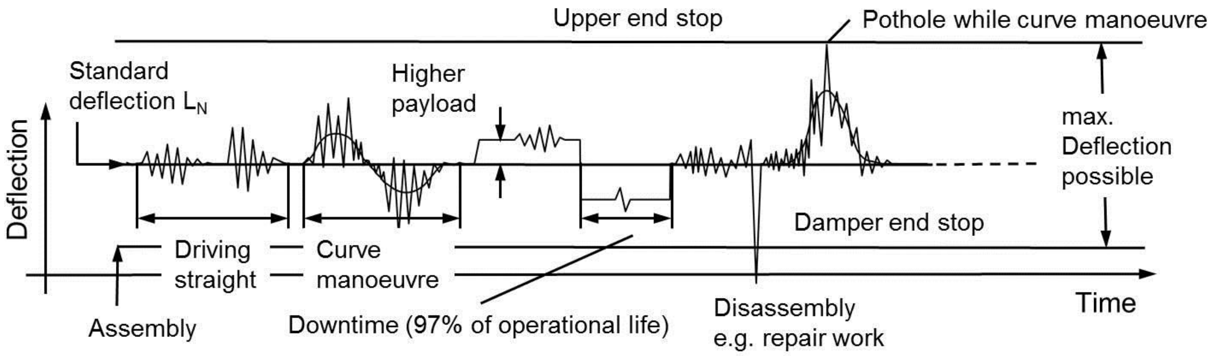


Figure 1: Schematic loading of suspension springs of passenger cars [1]

Besides the intended mechanical loads, springs are subject to environmental influences that can have a considerable impact on their fatigue life – in particular corrosion, pre-existing damage caused by grit and abrasive wear. These conditions have a reciprocal effect on each other and must be seen and tested as a complex load.[2] Abrasive wear caused by relative movement of the spring seat as well as grit impact compromise surface protection and accelerate corrosion considerably. The resulting decline in utilisable fatigue strength can only be determined in combined resonance tests.[3]

## 3. TEST IMPLEMENTATION

To systematically examine the different influences on the durability of springs, comprehensive test series were performed on items with a generic geometry, varying in manufacturer, material, production method and coating.

### 3.1. Test methodology

The tests were conducted at IABG's spring test centre using CSTM-type resonance spring test benches where two or four springs can be mounted simultaneously and compressed either in parallel or along paths according to the axle kinematics (Figure 2). A static pre-load is superimposed by cyclical loading that can be applied at a precisely set resonance frequency in a very energy-saving manner utilising the resonance magnification. Intermittent salt water sprays and optional blasts of suitable media simulate abrasive and corrosive environmental conditions.

Grit-induced surface defects were reproduced under realistic conditions and with utmost repeat accuracy in an IABG stone impact simulator, type GISM, in which springs can be exposed to projectiles at continuously adjustable speed (Figure 2).

Figure 2: IABG resonance spring testing machine and grit impact simulator

## 3.2. Test types

The experimental verification of fatigue strength must cover static and cyclical operational loads, abrasion, grit impact and corrosion. Therefore, test parameters were derived in comprehensive test series and matched against damage patterns found during road tests and in used vehicles. The test series included resonance tests carried out with static mid-loads in a corrosive environment. Some of the springs were damaged beforehand in a grit impact simulation at a predefined speed, an abrasion resonance test exposing the springs to dust, sand, stones and humidity, or by corrosive action with a static pre-load.

The mid-load and cycle stroke selected for a resonance test must ensure the minimum required test duration to simulate an effective corrosive attack. The state-of-the-art recommendation is a configuration of mid-load and cycle stroke that leads to a fatigue damage parameter of $P_{SWT} \approx 650$ to 700 MPa.[4)] The resonance frequency should range between 3.0 and 5.0 Hz. To ensure a minimum of statistical reliability, tests should be conducted for each loading level on at least eight springs.

The test programme described in this document included three types of fatigue tests (see descriptions below). All tests were carried out with a cycle stroke of 75% of the possible deflection around the spring's installation position plus intermittent salt water sprays at room temperature. In two cases, the springs were damaged prior to the test:

- Without premature damage
- With premature damage resulting from a grit impact simulation and four weeks of corrosive action with a static pre-load
- With premature damage by abrasive wear of the lower spring seat caused by exposure to various media and four weeks of corrosive action with a static pre-load

The abrasion of the protective coating of the area around the spring plate was simulated in a fatigue test without corrosive action at room temperature, whereby abrasive media such as sand or grit were repeatedly blasted at the lower spring seat. Resonant stress was generated by a load spectrum, representing the random-like series of high and low oscillation amplitudes and covering the maximum spring deflection.

Since the damage by grit impact strongly depends on the spring's mounting situation and the operating conditions, type and quantity of the projectile material as well as the direction and speed of the projectiles needed to be determined by matching the damage patterns against the road test results. To obtain an objective comparison of the damage caused during the test and the damage caused during vehicle operation, the superficial defects of the protective coating were counted and measured using a µCT image, and the results were plotted in a probability net (Figure 3).

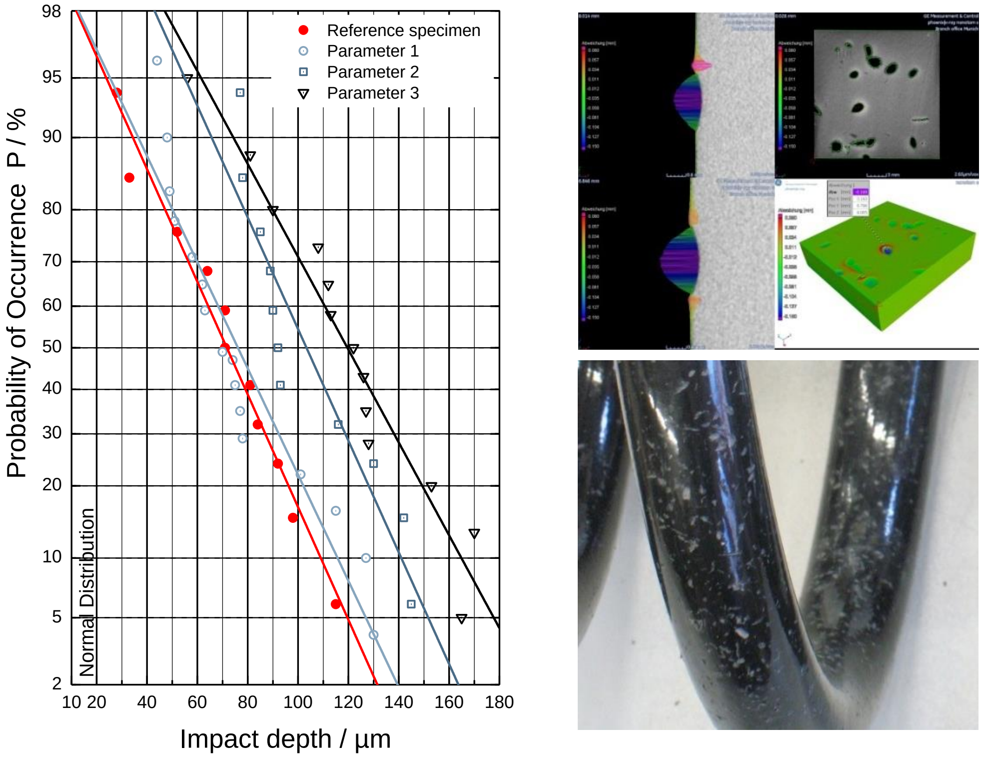


Figure 3: Result of grit impact measured by µCT depicted in the probability net [5)]

These are the conditions under which tests were conducted on springs produced with different manufacturing technologies, e.g. heat or surface treatment, that presumably have a direct impact on the strength, internal compressive stresses in the outer fibre and the structure of the base material. Tests also included studies of the influence of different coating systems used to protect the spring surface against damage and corrosion.

## 4. TEST EVALUATION

All fractured surfaces were analysed in terms of mode of failure, fracture position, cause of damage and crack initiation position. The average fatigue life was determined based on the logarithmised number of cycles, the scatter based on the logarithmised standard deviation.[6] The standard deviation is independent of distribution – the scatter, on the other hand, depends on the distribution model. The evaluations presented in this document assumed a normal distribution of the population, therefore the scatter $T_N$ was calculated as follows:[7]

$$T_N = \frac{x_{90\%}}{x_{10\%}} = 10^{2,56 * s_{lg}} \qquad \text{with}$$

$$x_{90\%/10\%} = lg\bar{x} \pm 1,28 * s_{lg} \qquad (1)$$

The numbers of cycles for fractures were plotted into a probability net with logarithmic normal distribution according to the following approximation equation for the probability of failure and approximated by linear regression.

$$P_{Fi} = \frac{103 * i - 37}{103 * n + 29} \qquad (2)$$

Incomplete tests were also entered into the probability net as per (2). Average fatigue life and scatter calculations should not include the numbers of cycles for test items that were not fractured throughout the entire test. Both values should rather be determined based on the linear regression of the numbers of cycles for fractured parts.

Figure 4 shows examples of a completed and an incomplete random test, depicted in the probability net of the normal distribution.

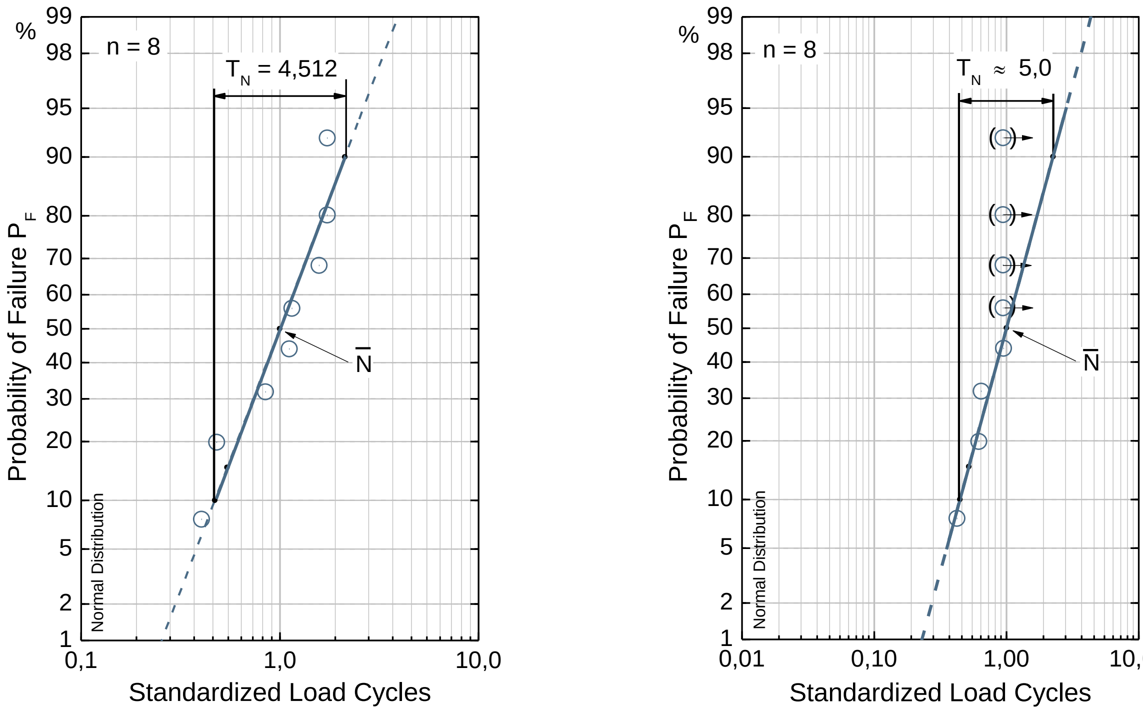


Figure 4: Test results depicted in the probability net [8]

## 5. TEST RESULTS

### 5.1. Metallographic and fractographic findings

Springs fractured during the tests and differing in terms of numbers of stress cycles (low, high), macroscopic fracture position and applied manufacturing technologies were selected for a fractographic surface evaluation.

Examinations under the scanning electron microscope (SEM) showed that all fractures on the selected springs were initiated either on or slightly below the wire surface. All in all, the analyses revealed two distinct damage mechanisms. Besides typical fatigue fractures, approx. 40% of the examined surfaces showed signs of corrosion fatigue. The cause and extent of the damage depended on:

- Material purity (non-metallic inclusions and shrinkage holes) [9)]
- Manufacturing influences (course, fissured wire surfaces caused by over-blasting, oxide lines or material displacements caused by excessive milling, for instance)
- Environmental influences (mechanical damage to the protective coating or spring surface, corrosive action)

Typical SEM findings are shown in Figure 5. Metallographic studies of polished wire cross-sections confirmed the fractographic findings.

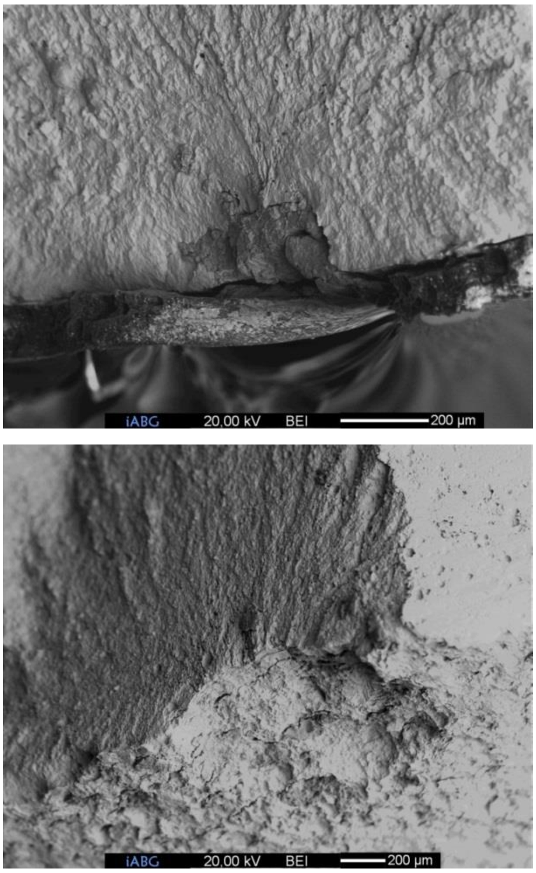


Figure 5: SEM of shrinkage hole (upper) and corrosion pit (lower) [8)]

To examine the influence of different manufacturing technologies, the fatigue strength of the wire cross-sections was determined using the Vickers micro-hardness test method. Each of the selected technologies yielded different hardness profile values and trends, and often the hardness peaks were not detected at the wire surface but roughly one millimetre below.

Some springs were manufactured using different types of shot-peening. By means of x-ray diffractometry, residual-stress depth profiles were established for selected springs. The internal compressive stresses measured on the surface rose with increasing depth and reached a maximum of up to -1100 MPa approx. 100 µm below the wire surface. The internal stresses equalised at depths ranging from 200 to 400 µm max. Results varied depending on the respective spring manufacturer.

Defects larger than approx. 200 µm on or below the wire surface initiated cracks, irrespective of how they were originally caused. Besides surface defects resulting from manufacturing and production errors as well as non-metallic inclusions, test-induced corrosion pits were the most frequent triggers for fatigue fractures or corrosion fatigue.

### 5.2. Durability

The tests illustrated the distinctive influence of premature damage by grit impact and abrasive wear on the fatigue strength of coated springs under corrosive environmental conditions. They showed that advance simulation of wear through friction around the bottom spring coil and corrosive action can shorten the fatigue life considerably compared to a resonance test with exposure to corrosion only (Figure 6).

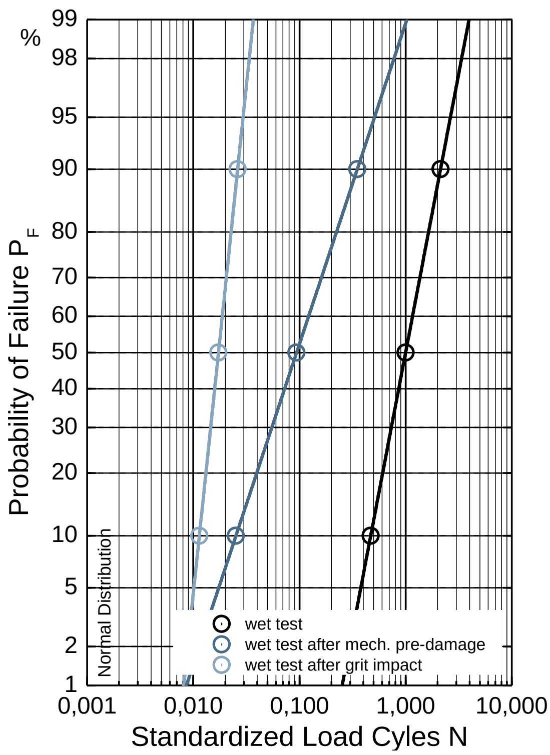


Figure 6: Influence of pre-damaging on the fatigue strength of springs [8)]

The abrasion damages the spring's protective coating and exposes the wire surface to corrosive effects of the environment. This form of deterioration can initiate fractures. Springs with few signs of abrasion sometimes have a shorter fatigue life than springs with more noticeable signs of abrasion and large unprotected areas. The resonance test with advance grit impacts and corrosive action yields the shortest fatigue lives. The tests prove how significant the surface coating is for the fatigue life of a spring that has been prematurely damaged and exposed to corrosive conditions. In all tests, modifications to the protective coating were the most effective measure to increase fatigue life. Modifying the coating results in a 6 times longer fatigue life than with standard varnish, for instance. Figure 7 compares the results of the resonance tests with advance abrasion and stone impact in a bar chart. Each bar represents a certain type of spring by three different manufacturers. Springs with a modified protective coating have an unmistakably higher average fatigue life than springs with a standard coating. This effect is proven both by the resonance tests with advance grit impact and by the simulation of wear through friction around the bottom spring coil and subsequent corrosive action.

Improved protective coating can better withstand the two mechanical stresses mentioned and reduces the impact of corrosion on the damaged area considerably. It was also observed that the premature damage by grit impact led to a more significant reduction in fatigue life than advance damaging through abrasion.

The influence of manufacturing technologies on the durability of pre-damaged springs exposed to corrosive conditions is secondary in comparison to the significance of the surface coating.

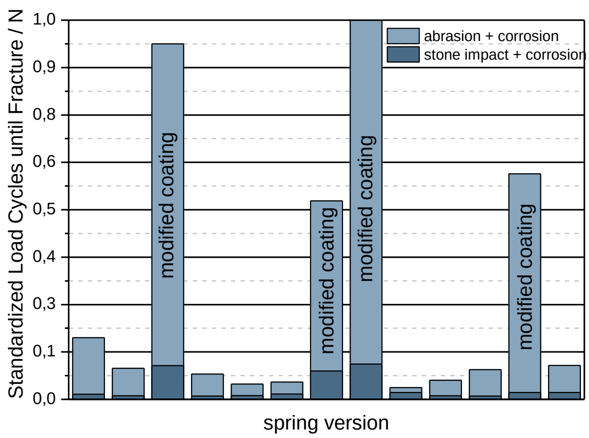


Figure 7: Test results of cyclic test with abrasion/grit impact and corrosion [8)]

## 6. CONCLUSION

For the purpose of systematically examining the fatigue strength of coated vehicle springs under realistic environmental conditions, reproducible parameters for premature damage and durability tests were determined and then compared with road test results. Comprehensive durability tests on generic springs manufactured with different technologies and coatings enabled the verification and quantification of the dominant influence of advance mechanical damage by grit impact and abrasion on the fatigue strength under corrosive conditions. Corrosion pits combined with advance mechanical damage to the spring surface reduce fatigue life significantly. An effective countermeasure is to improve surface protection. Optimised manufacturing technologies such as surface or heat treatment, on the other hand, have a secondary influence on the fatigue strength under realistic testing conditions.

While the test parameters were matched to damage patterns detected in the field, the results provide only a relative comparison of the individual coating systems. The study of the relationship between test and real operating conditions has not been completed and should be continued.

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