Suspension Springs – Experimental Proof of Reliability under Complex Loading

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Abstract Fatigue strength of suspension springs in service life is subject to numerous influences. Besides the mechanical loading, determined by the kinematics of the suspension system, road conditions and driving maneuvers, fatigue strength of suspension springs is vitally affected by material properties, coating and environmental influences. Typical failure modes of suspension springs and their causes can be divided into several groups like static and cyclic loads, geometry and dimensions, manufacturing influences, mechanical defects of coating or steel surface, corrosion, fretting corrosion and imperfection of steel purity. This paper covers the influence of mechanical loading taking into account the influences of the kinematics of the suspension system, environmental conditions and steel purity. This leads to a comprehensive experimental validation strategy for suspension springs. Also statistical effects are discussed that have to be taken into account for a safe proof out.

Keywords Suspension springs, fatigue, corrosion, steel purity, testing

1. Introduction

Springs are used in many technical applications and play a vital role as elastic elements. In passenger cars, steel coil springs are used widely as suspension springs and as valve springs. Their durability in these cases is vital for the safety and reliability of the vehicle. Therefore, failure of suspension as well as of valve springs must be avoided with a high level of safety. For this, dedicated concepts for design and proof out are necessary.

In this paper, the relevant service loads acting on suspension springs of cars will be shown as well as pictures of typical failure modes. Besides a description of the failure modes leading to a defect of a suspension spring, a concept for proof out of suspension springs will be discussed, taking into account fatigue due to mechanical loading under corrosive media, contact and abrasive wear and damage due to grit impact. Finally, a concept for proof of steel purity is shown.

This paper is focused on coil springs used in passenger car suspensions. However, the methods may be used for evaluation of others springs in other applications with adaptions that take into account the differences in the respective application.

2. Material, Design and Conditions of Installation

Suspension springs of ground vehicles are subject to high static and cyclic loads. In order to realize the wanted stiffness characteristics within a minimum of designed space and mass, high strength steels like 52CrMoV4 or 54SiCr6 with a tensile strength of 1400 up to 2000 MPa are widely used. The local stresses acting in the springs are very high with a high frequency of occurrence. The sensitivity of steels to stress concentrations due to notches increases with increasing tensile strength and yield ratio. Therefore, springs made out of high strength steels will be sensitive to defects on the surface that may be caused by the production process, grit impact, abrasive wear or corrosion.

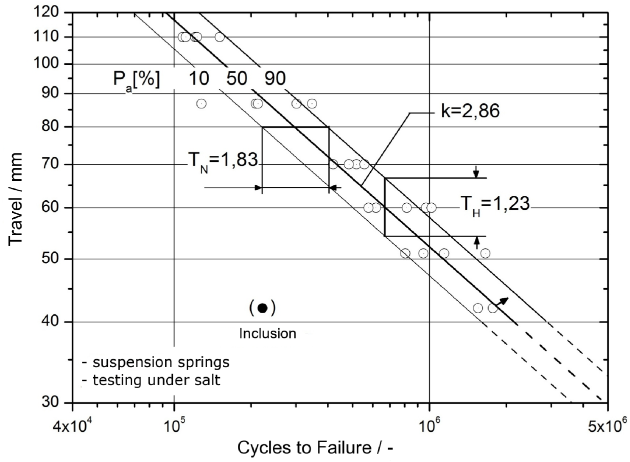

Figure 1. Failure caused by discontinuity of microstructure (inclusion) [2]

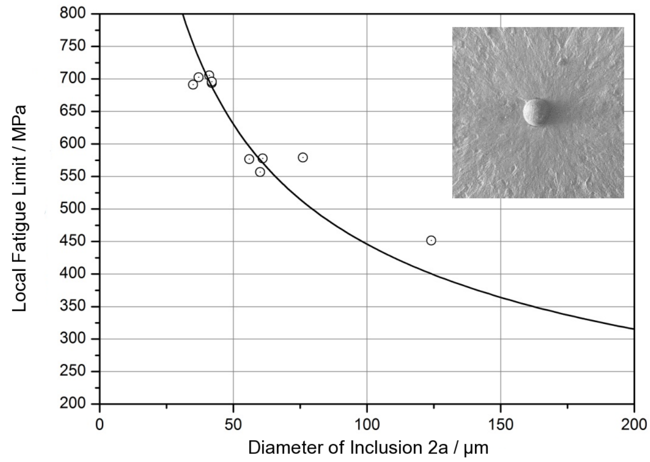

Figure 2. Influence of size of non-metallic inclusions on local fatigue limit [1]

Also, nonmetallic inclusions or other imperfections within the material may cause a failure, especially under high cycle fatigue loading. The combination of high local stresses and defect size may lead to stress concentrations above the threshold value for crack propagation. Hence, a material defect can act as an initial crack, propagating under cyclic loading and leading to a failure of the spring (see Fig. 1). In [1], the influence of nonmetallic inclusions in high strength steels was investigated in a comprehensive way yielding a correlation of the size of inclusion and upper boundary of possible fatigue limit (see Fig. 2). For the design of springs made from high strength steels, this means that the higher the used stress level and therefore the necessary strength level of the material, the more critical steel purity must be taken into consideration in testing for development, qualification and quality assurance. Since nonmetallic inclusions usually follow a different statistical distribution than the cyclic strength values of the base material, these have to be taken into consideration separately. Whether an impurity in the material will be critical for the endurance of a spring, does not only depend only on the size of the impurity but also on its location within the spring, since crack propagation will only occur, if there is a high local stress level at the location of the defect. This fact must be considered with respect to the critically stressed material volume and the statistical size effect. Detailed description on this can be found in [2].

With high strength steels in suspension springs of ground vehicles, special focus must be set on the risk of stress corrosion cracking. This effect may not necessarily depend on a higher tendency for corrosion of the used steel. It may also be caused by the high local stresses in combination with the notch sensitivity of the material. In order to decrease the risk of stress corrosion cracking, nowadays suspension springs are coated with specialized coating systems. Not only do these coatings prevent the spring from corrosion but also from other surface damages like grit impact.

The local stresses acting within a coil spring depend mainly on the geometrical design, the axle kinematics and the load applied. Also the local design, stiffness and surface properties of the spring attachments do influence the local stresses and the risk of abrasive wear and corrosion in the contact area of springs and spring attachments. While in a MacPherson strut, the upper and lower spring attachment will only move in a linear displacement (parallel deflection), in twin lever axle kinematics, also a lateral displacement as well as a rotation between the upper and lower spring attachments usually occur (circular deflection, see Fig. 3). Off course, this will yield different local stresses in the springs. The geometric design as well as the stiffness of the upper and the lower spring attachment as well as the geometric design of the first and last winding of the coil spring can significantly influence the local stresses in this critical area. These effects must be considered both in the design as well as in the validation process of a spring. The design of the spring attachment does not only influence the local stresses within the spring in the contact area. It also influences the abrasive wear on the spring coating in the contact area, especially in the lower attachment. Especially under corrosive media, the contact area plays a vital role for the fatigue live of a coil spring. Springs that may be deflected up to block experience contact wear at the areas of contact. This also may damage the coating and enable corrosion on the spring.

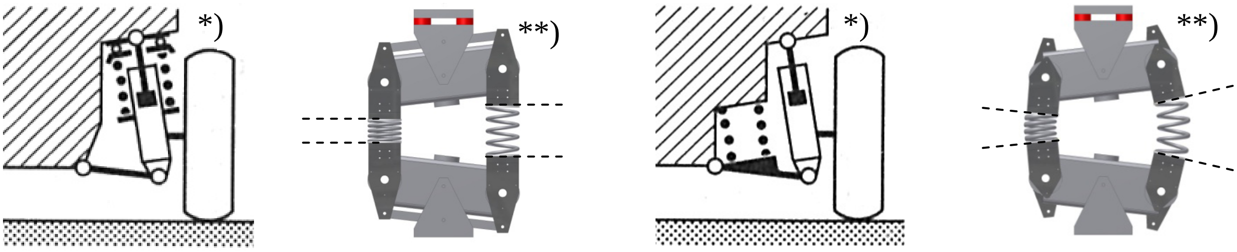

Figure 3. Kinematics of parallel and circular deflection in car suspension and test facility (* [3], ** IABG)

3. Service Loading

Besides geometry, material, production and conditions of installation, the loads and environmental conditions in service determine the service life of springs. The mechanical loads consist of a static preload and superposed cyclic loading. Fig. 4 gives a schematic overview of a typical load history of a suspension spring of its lifetime in a vehicle, beginning with its installation.

Maximum and minimum deflections are determined by the conditions of installation and the axle kinematics. The static preload consists of the preload due to mounting and the preload of the proportional weight of the car. This typically causes car springs to experience cyclic stresses with a high mean-stress. The cyclic loads are caused by driving maneuvers and surface roughness. A typical passenger car will only be moved for about 3% of its service life (counted in days rather than number of cycles). Hence, also effects acting during the 97% of time when the car is parked must be taken into account, since stress corrosion cracking may also act in these periods.

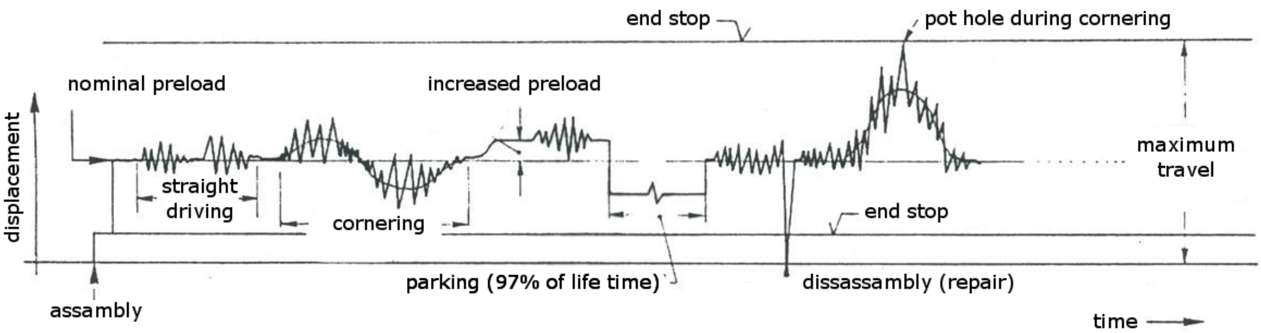

Figure 4. Schematic loading of suspension springs of passenger cars [4]

The cyclic loading of a spring consists of a variety of load cases (see Fig. 4). While cruising on paved roads will cause low to middle load amplitudes, driving on rough roads or off road, dynamic cornering and special incidents like driving through a pothole or over speed bumps will cause much higher loads that also have to be safely taken into account. Also, combinations of different maneuvers must be considered, such as high vertical dynamics due to rough road surface while taking a sharp corner at high speed. Thus, the full possible travel of the spring, from fully extended to fully compressed, usually is covered. For a safe and still economically sensible design and test strategy, both amplitudes as well as number of occurrence of the different load cases must be investigated by means of extensive road load measurement, road data profiling, multi body simulations, statistical evaluation and extrapolation of the respective results (see also [5]).

Besides mechanical loading, suspension springs in ground vehicles are subject to environmental and service conditions that may influence the service life especially of high strength springs significantly [4]. In many regions, corrosive media are present on the roads at least temporarily. Anything from normal humidity over rain to salt water will be found during driving cars on roads all over the planet. Hence, corrosion can act on the springs if they are not covered by a durable coating. Especially during winter periods, grit that hits the springs may damage this coating making its protection void. Additionally, micro mechanical relative movement in the contact region between spring and spring seat will cause abrasive wear on the coating. This effect may be intensified, if abrasive media like grit or sand are cumulated in the lower spring seat. Due to the permanent static pre load due to assembly and car weight, springs are under a constant pre-stress, thus being subject to the threat of stress corrosion cracking. This threat is significantly higher under the conditions described.

The influences shown on the service life of suspension springs in ground vehicles under cyclic loading are not independent from each other. For example, the influence of corrosive media is much stronger, if the coating of the spring is damaged due to grit impact. Hence, the combination of load influences must be regarded as a complex load scenario in design and testing in order to cover the combined influences.

In commercial vehicles, especially in heavy trucks, leaf springs rather than coil springs usually are used in the suspension. Here, besides the influences described above additional effects may be important. Leaf springs usual front axles of commercial vehicles are subject to additional load cases such as torsional deformation due to vehicle roll and driving over single sided obstacles or S-shaped bending due to breaking moment [11, 12]. These have to be taken into consideration in design and testing.

4. Failure Modes

Coil Springs in passenger car suspensions show a number of typical failure modes, caused by material defects, the production process and complex service loading. Often, failures are caused by a combination of influences. Surface damage due to grit impact and abrasive wear together with corrosion may initiate crack propagation finally yielding a defect of the spring.

The most common failure mode of suspension springs of ground vehicles is the formation of fatigue cracks initiated from surface defects. The high strength steels used for these components are very sensitive to any geometrical or metallurgical discontinuity. In the sense of fracture mechanics, these can be interpreted as cracks. Making use of the potential of the high strength steels used for suspension springs, high local stresses will be allowed in the springs, yielding high stress intensity factors at these cracks. If the threshold value for crack propagation is exceeded, the cracks will propagate under the cyclic loading causing a failure of the component. Fig. 5 shows a typical failure of a suspension spring of a passenger car starting from a surface defect.

Another failure mode is shown in Fig. 6. Here, a fatigue crack started from a non-metallic inclusion below the surface of the spring. Since these internal defects will only lead to a propagating crack, if the threshold value for crack propagation is exceeded, they will only cause a failure, if they are located in a highly stressed volume of the spring. Hence, the frequency of occurrence of this failure mode is smaller than the one of defects on the surface, where local stresses are naturally high due to the stress distribution over the cross-section under combined torsional and bending loading. Reports about failures due to internal defects can be found e.g. in [6] for coil springs and in [7] for leaf springs. These failures follow a different statistical distribution then failures due to surface defects (see Fig. 1). In component testing, this effect is difficult to cover because of the low probability of occurrence, hence special test methods and statistical evaluation should be used as described in [2].

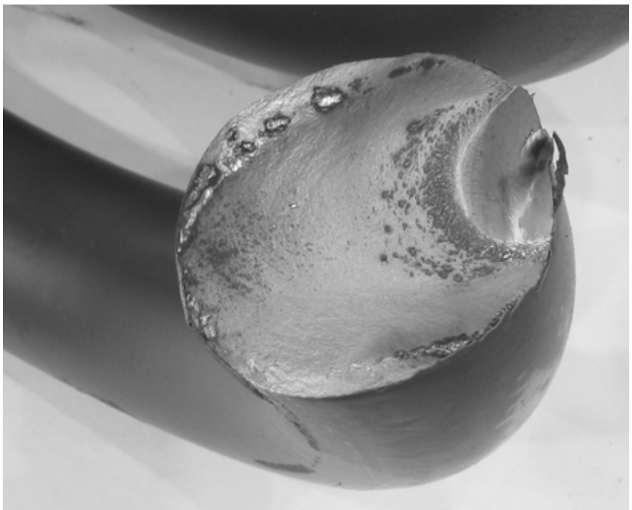

Figure 5: Fatigue fracture of suspension spring initiated at surface [8]

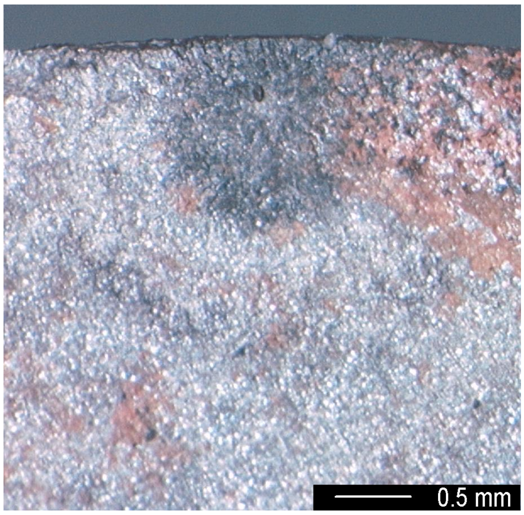

Figure 6. Fatigue fracture of coil spring initiated at non-metallic inclusion [IABG]

Harsh environmental conditions may decrease the cyclic strength of a spring considerably. Grit impact, abrasive wear and corrosive media can form defects acting as starting crack yielding a component failure. Fig. 7 shows a typical fracture surface of a suspension spring. The crack started from a surface defect under corrosion and propagated under cyclic loading. The significant influence of corrosion on the cyclic strength of high strength springs is shown in Fig. 8. Here, numerous springs where tested with constant amplitude cyclic loading in dry air and under a 5% NaCl-solution that was sprayed on the specimens intermittently. The test results were statistically evaluated. For a clearer picture and a better understanding, only the regression lines are shown.

Taking the S-N-curve of the test results under “dry” laboratory conditions as a reference, the influence of corrosion due to salt water can be seen for uncoated springs, coated springs without pre-damage and coated springs with pre-damage due to grit impact. All tests were performed on IABG Corrosion Spring Testing Machines (Fig. 9). The grit impact was generated with an IABG Grit Impact Simulator. The test parameters for grit impact as well as for corrosion were optimized in order to reproduce typical effects as can be seen on springs under service loading for longer periods. It is apparent that corrosion can decrease the cyclic strength of a high strength spring significantly. The effect can be reduced considerably by application of adequate surface coating, but cannot nearly be eliminated. If the surface coating is pre-damaged by grit impact, the better part of the positive effect is lost again. Also note that in all cases, up to $2 \cdot 10^6$ load cycles, no clear endurance limit can be found when testing in corrosive environmental conditions.

Taking into account these results, it is clear that for safe evaluation of the cyclic strength of suspension springs in ground vehicles, a combined test procedure must be defined and obeyed that covers all the effects described. Cyclic testing in dry laboratory conditions still may be very helpful for a first evaluation and optimization of geometry, material and production process. A final qualification test however must also contain grit impact, abrasive wear and corrosive media.

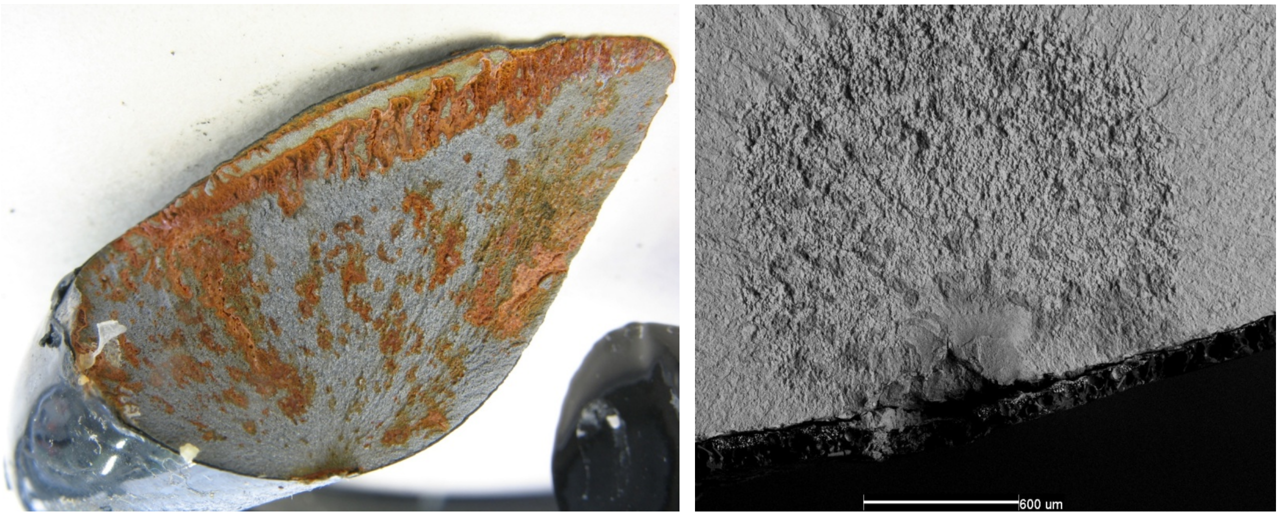

Figure 7. Fatigue fracture initiated by a corrosion pit [8]

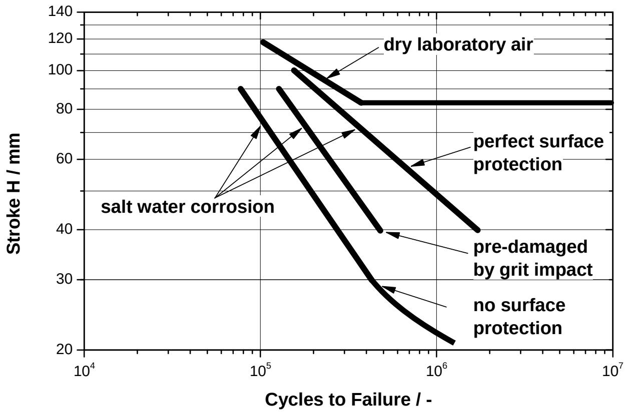

Figure 8. Influence of corrosion and pre-damage on fatigue behavior of suspension springs [9]

Figure 9. Corrosion Spring Testing Machine [IABG]

5. Experimental Proof of Service Strength

A test concept for suspension springs of ground vehicles has to cover all failure modes with the required safety factors in order to limit the probability of failure to an acceptable minimum. Here, a separate definition of development and qualification tests may be reasonable. While development tests may be performed on specimens from the raw material or generic spring geometries in dry laboratory condition, the authors strongly recommend a comprehensive test program with the specific springs from the series production process for a final qualification test.

For evaluation of raw material and semi-manufactured products like the spring wire, the usual tests for static properties like yield strength and ultimate tensile strength etc. should be amended by tests for cyclic properties in order to securely assure the cyclic strength and the steel purity. Fig. 1 shows test results from a large test program where only 1 out of 120 springs failed due to a non-metallic inclusion at very low load amplitude. This is equivalent to a probability of failure of 1 out of 30 cars (usually having 4 springs each), which surely is not acceptable! These inclusions can very hardly be found with component tests. Due to the inhomogeneous stress distribution, only a small portion of the volume of a coil spring is loaded to local stress levels at which a crack will propagate starting from this inclusion. In order to investigate steel purity, special cyclic tests are recommended using specimens with a high critically stressed volume in order to facilitate the finding of the largest size of inclusion with an affordable effort for testing [2].

To investigate the steel purity in an efficient and safe way, a test machine and test method was developed at IABG using dedicated specimens that cover the critically stressed volume of about 50 springs with only one test. This test does not depend on a specific geometry of a spring and is recommended as development and acceptance test for raw material and semi-manufactured parts like spring-wire. It is much more reliable than the commonly used method for determination of steel purity only based on the analysis of metallographic specimens [2].

To the authors' knowledge and believe, the fatigue strength of a high strength coil spring for use in the suspension of a ground vehicle can only be safely approved, if tests on series production parts are performed in realistic installation conditions (original spring seats and orientation). A simulation of the axle kinematics with special focus on the deviations and deflections of the spring seats in both limits of travel is mandatory. The environmental conditions consisting of corrosive and abrasive media have to be simulated. If the risk of grit impact cannot be eliminated during service life, testing of springs that have undergone a grit impact simulation prior to the fatigue test in corrosive environmental conditions is mandatory. Only with this combined test procedure, realistic results can be obtained that allow for a safe evaluation of the service strength in field use.

A complete simulation of the axle kinematics containing all boundary conditions may be performed in a front or rear axle test facility. However, installation and running costs of these test facilities are very high and a lot of car components are needed for the test that may not be available at the time of testing. Moreover, a specific variation of test parameters in order to investigate the influence of single parameters often is difficult or not possible. Therefore, Resonance Testing Machines are commonly used for testing of coil springs, since they combine extremely low energy consumption, high reliability and a minimum of effort for the single test setup. Using an adjustable axle geometry simulator, the kinematics of the real axle can be reproduced. Corrosive environmental conditions can be generated in a realistic way by a facility for supply and intermittent application of salt water. Abrasive wear can be simulated by application of abrasive media at the lower spring seat where the media would also accumulate in real field use. Hence, all influences that are relevant for the fatigue life of suspension springs under complex loading can be simulated in a precise, effective and cost saving way (see Figure 9).

The number of specimens to be tested as well as the test spectra and the parameters for pre damage, simulation of corrosion and abrasion must be determined in a way that the different types of field use are covered with a high level of certainty, yielding test results correlating well with field experience. To cover statistical effects, the number of tests, the selected test amplitudes and the method for statistical evaluation of the test results must be described precisely.

An example for a description of a qualification program for coil springs was defined by German OEMs in the working group for springs and stabilizer bars [10]. To avoid incidental failures from non-metallic inclusions, the authors additionally recommend a test of the raw material or the half manufactured product for steel purity as described in [2]. A continuous adaption of the test parameters to new information from field use should be performed in order to always keep the test procedure up to the level of technology. A comparison of tested samples with parts from field use can be used to scale and adapt the test parameters in order to generate test results correlating with field use in an optimized way.

Depending on the focus of investigation, research tests may be performed on generic test samples. 360°-sections from cylindrical coil springs have proven a good sample geometry since they can be reproduced with a minimum of manufacturing costs for the samples. With a special Resonance Testing Machine for single coils, specific influences of e.g. material, heat treatment and shot peening can be studied using generic specimens. Compared with tests on designed to specification coil springs, tests on generic test springs can be performed with identical geometry of test sample providing comparable test results over a very long period time. However, the different stress distributions in a single 360°-section and the spires in complete coil spring must be taken into consideration in definition of the tests and in interpretation of the test results.

6. Conclusion and Outlook

It has be shown that for safe qualification of fatigue strength of suspension springs in passenger cars, a test program must be specified and performed consisting of test of series production springs under cyclic loading with simulation of the axle kinematics, environmental conditions and pre-damage. Additional test on specimen for the proof of steel purity are recommended by the authors. This is especially important for springs made out of high strength steels in order to fully make use of the potential of high strength materials with a maximized reliability. For quality assurance, mechanical testing of samples for steel quality as well as testing of springs from series production is recommended.

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