Fatigue Design of Leaf Springs for New Generation Trucks

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Abstract. Taking as example high-performance parabolic leaves made of the high-strength steel 52CrMoV4 used for the suspension of heavy truck axles, the present paper focuses on the effect of the manufacturing process (heat treatment and stress peening) on their performance under fatigue loading. Investigations of the microstructure and the mechanical properties of the core and the surface of selected prototype specimens reveal the degradation of the mechanical surface properties due to the applied manufacturing process. The results of these investigations have been used as input for analytical fatigue life calculations and the theoretical assessment of every individual life-influencing factor (material, heat treatment, surface treatment, loading). Wöhler (S-N) curves for various probabilities of survival were experimentally determined and compared to the calculated ones. The agreement between Experiment and Theory is satisfactory.

1. Introduction

Nowadays, leaf springs constitute the most effective suspension way of light- to heavy-duty commercial vehicles. Their outmost advantage is that they group together all main operational actions (i.e. suspension, lateral support and guidance) into a single component, rendering a large number of additional components redundant. On the other hand, this creates the need for a detailed and accurate design and a consequent reliable manufacture of components able to withstand these actions. Previously published papers [1,2] have already covered some of the most important design aspects of leaf springs, namely the strength and fatigue performance for a set of specifically determined fatigue-related properties, as well as the design aspects concerning the kinematic behavior (guidance to suspension coupling). An exemplary overview of a leaf-spring-based suspension system for the front axle of a heavy-duty truck is illustrated in figure 1. Therein, the various components constituting the suspension, guidance and braking sub-systems are clearly indicated, as well as the main load components, which act upon operation.
Rather than examining the overall design process (alike the previous contributions [1,2]), the present paper attempts to go deeper into the indispensable design input data, by taking a closer look to the above-stated set of strength- and fatigue-related properties. Hereby, these very properties and basic technological factors, which act together as fundamental perquisites for the design itself, are approximated through some basic material and surface properties related to the specific manufacturing processes used during the production of high-performance leaf springs.

More specifically, the present study focuses on the influence of the manufacturing process on the microstructure, and the mechanical and surface properties dominating the resultant fatigue life of parabolic leaf spring specimens made from the typical leaf spring steel 52CrMoV4 (Material number 1.7701 acc. to EN 10089: 2002 [3]). This process involves a series of different procedures, namely the transformation of the raw material microstructure through quenching and tempering, the stress-shot-peening of the failure-critical surface and finally the normalization of the induced residual stresses over the aforementioned surface through a “controlled” plastification procedure.

The inspection of samples (leaf spring samples produced in serial conditions) under the Optical Microscope has revealed the microstructure and the surface decarburization state owed to the heat-treatment process. Vickers’ (HV) micro-hardness profiles were measured to verify the above findings (extent of the decarburized zone), while Rockwell C (HRC) macro-hardness measurements over the surface and core of the samples were used to evaluate the fundamental strength properties resulting from the manufacturing process altogether. Additionally, surface roughness profiles were determined to quantify the influence of the technological parameter concerning the roughness caused by the Stress-Shot-Peening (SSP) process on the overall fatigue behavior.

Using these carefully resolved technological parameters in conjunction with the material’s mean stress sensitivity approximation formula after Schütz [4], theoretical fatigue life calculations for parabolic leaf spring specimens made of the 52CrMoV4 high-strength spring steel have been performed based on the FKM guideline [5] along with some inevitably arbitrary assumptions (but in line with the accumulated experience [1,2]). The influence of every individual factor was successfully identified and assessed in respect to the total fatigue life estimation, while uniaxial cyclic, constant-amplitude, three-point bending tests were conducted on a series of specimens, in order to determine the fundamental stress-life curves for various probabilities of survival and validate the accuracy of the respective theoretical calculations. Finally, a limited set of variable amplitude loading tests following the
operational loading spectra after Grubisic and Fischer [6] have been used to check the accuracy of the developed theoretical stress-life curve in conjunction to the Miner’s elementary rule, assuming a damage sum of D=1 (100%).

2. Production stages of leaf springs

The raw material 52CrMoV4 used for leaf spring production comes into flat bars (geometry and dimensions acc. To EN 10092:1 [7]) with an original bainitic-perlitic dominant microstructure. These bars are initially heated up to >900°C and rolled in order to achieve the desired thickness distribution along their length (it should be mentioned at this point that due to the similarity of the function which describes the desired thickness distribution, to the mathematical parabolic function \( f(x) = \frac{a}{x^2} \), \( a = \text{const.} \), the leaf springs of this type have acquired the characteristic designation “parabolic”). Other areas that need geometrical forming, i.e. steps and eyes (see also [1,2]), are created at this stage as well, using forging moulds and specialized forming machines (for eye forming). Each leaf, which is still up to this point almost a straight bar, is then inserted into another forging press that will give it its characteristic elliptical shape shown in figure 2.

Figure 2: Unloaded mono-leaf spring illustrating its characteristic elliptical shape

The next phase comprises of the quenching of the leaf in a temperature-controlled oil bath in order to achieve a cooling gradient that will transform the microstructure to almost a 100% martensitic one over both the surface and core. The leaf is then tempered in a controlled environment (the whole procedure is commonly referred to as martensitic quenching and tempering) to relax the internal stresses induced by all previous actions (severe hot-rolling, forming and quenching) and regain some ductility. The side effect of this mandatory annealing is the formation of a decarburized zone on the surface of the leaf, which is both unfavourable, but also somewhat desired (up to a certain extent) in terms of fatigue. In order to understand this ambiguous behaviour, one must go further than the obvious reduction in hardness and consequent lower material strength (lower ultimate tensile strength \( R_m \)) owed to the expulsion of carbon from the surface, and realize that the impelled increase of the ductility can offer an enhanced crack resistance in fatigue loading. Therefore, it becomes evident that the sequential heat-treatments should be balanced to achieve an optimum behaviour overall.

The next production stage of each leaf includes the bending of the leaf near the material’s nominal tensile strength (~1600-1750MPa) using a designated actuator, its insertion to a “cassette” that will hold this bent position in place and the shot-peening of the tensile surface of the leaf (upper surface in Figure 2) with shots of certain hardness and diameter. The goal of this “stress-shot-peening” process is the entrapment of favourable compressive residual stresses that will decrease significantly the maximum effective stress (the stress that the material on the surface of the leaf is subjected to during operation) and hence increase the fatigue life. Common compressive residual stress values induced by this procedure range from 550 (quite bad quality) to 1200MPa (superior quality), which demonstrate the importance of this stage [1,2].

Again, an unfortunate side effect of the later procedure is the formation of increased roughness, which has the opposite outcome. Regarding this point, it should be mentioned that studies on the intensity, coverage and number of passes of the shot peening process [8] have shown that the roughness can be brought back to its original state or even achieve a better roughness profile, but in the expense of the total product cost (more than one passes). Thus, such methods (multiple passes) have not been adopted yet by the leaf spring industry.

Finally, the last stage involves the “pre-setting” of the leaf spring after its assembly (in case of multi-leaf springs), which is the bending of the spring to the extent of going over the material’s yield stress at
the tensile surfaces of all leaves, in order to evenly redistribute the above stated residual stresses. This action also serves the avoidance of the suspension’s settling and shagging after only a small portion of its operational life, since a relaxation and redistribution of stresses is otherwise inevitable.

3. Material microstructure and mechanical properties & Surface inspection
Extracting material samples from both the tensile surface and core of the specimens has enabled the inspection of the influenced areas by the heat- and surface- treatments. The metallurgical inspection under the Optical Microscope (OM) has revealed the almost 100% martensitic microstructure at all areas (core and surface), as well as the extent of the anticipated decarburized zone to a depth of about 150μm from the surface. Vicker’s micro-hardness measurements at the same area have verified this finding as illustrated in figure 3, which presents an exemplary area near the surface, along with the micro-hardness diagram over the depth (distance from surface). The decarburized zone becomes evident through editing the OM photo to offer a better view of the decarburization intensity (white areas indicate the absence of carbon).

![Decarburized zone over the depth near the surface and Vicker’s micro-hardness profile](image)

Figure 3: Decarburized zone over the depth near the surface and Vicker’s micro-hardness profile

As expected, the decarburization intensity varies from an almost complete (adjacent to the surface) to a partial one, which gradually fades away along the depth. The micro-hardness profile illustrates the respective behaviour, following an increasing function (from surface to core) up to the maximum of 500-530HV. These values coincide with the measured core hardness and comply with the almost martensitic microstructure of the core of the specimen, as shown in figure 4. The later figure is displayed hereby in order to additionally verify the uniformity of the material after quenching and tempering along the whole thickness of the leaf and to illustrate the solid quality of the microstructural grid (evenly distributed phase areas).
Rockwell C (HRC) measurements over the surface and core of the samples present an almost uniform behaviour in hardness, with a tendency of achieving a slightly higher value on the surface (core hardness ranges from 47.4 to 48.7HRC while surface hardness has an average value of 49.5HRC). According to the hardness-to-R_m conversion standard [9], the surface hardness corresponds to a \( R_m \approx 1728 \) MPa, representing the failure-critical area of the leaf spring and is therefore used to evaluate the respective material properties.

Finally, the surface roughness profile is measured in various locations to acquire the strength related roughness parameter \( R_z \) (peak-to-valley height) to be used in the fatigue life calculations. An exemplary measurement of the roughness profile is illustrated in figure 5, indicating the characteristic \( R_z \) value of 32\( \mu m \).

4. Fatigue life theoretical calculation
The primary target of the theoretical fatigue-life calculation is to develop a reliable stress-life curve for a constant stress ratio \((R = \sigma_{min}/\sigma_{max})\) or a better-suited in this case constant mean stress \(\sigma_m\), and constant amplitude loading (Wöhler curve). This can be achieved by determining at least two points of interest that a line can pass through. These two points are obviously the well-established fatigue limit \( (N_D = 10^6 \) cycles) on the one side and another one that corresponds to a different characteristic behavior, i.e. the knee point that corresponds to the initiation of the low cycle fatigue regime. Regarding the first point, a combination of the instructions found in the FKM guideline [5] with the option to include the Mean Stress Sensitivity factors established by Schütz [4] (instead of the FKM guideline proposed ones), can lead to a reliable estimation. On the other hand, no clear guidance is given anywhere for the determination of any other point of the fatigue-life curve, hence some improvisation is required.

Taking into consideration the expected stress-strain behavior of such a material (adjacent values of \( R_m \) and yield stress as well as limited ductility) one can speculate that the yield stress will be around the 90% of the \( R_m \). Therefore this value \((0.9 \cdot R_m)\) can be selected as characteristic and paired to an arbitrarily chosen fatigue life that respects the limited ductility assumed, i.e. \( N = 10^5 \) cycles. The later selection, although seemingly completely arbitrary and unreliable, is actually in accordance with the NASTRAN FE solver assumptions [10] used for many years now, while it has been additionally ascertained by own experience by its well-suited conformity to a vast number of experiments. Moreover, it can be easily
realized that the selection of this point inside the area of N=10^3 to N=10^4 cycles has, in all cases, a minor effect on the fatigue life curve slope.

Having drawn the line passing through these two points (line 1 in figure 6), the FKM guideline instructions are sequentially applied, starting by applying the material related factors (loading mode, roughness and residual stresses) and afterwards the load-level-related ones (mean stress sensitivity factor). This means that the whole line is first shifted upwards to account for bending (original fatigue limit is given for tension-compression) by a factor of 1.016 (line 2 in figure 6) and then downwards to rationalize the measured roughness (hereby a factor of 0.691 for Rz=32 μm – line 3 in figure 6). The maximum factor of 1.3 according to the FKM guideline is then selected to multiply the stresses and consider the effect of the favorable compressive residual stresses (line 4 in figure 6), since the guideline includes only the effect of normal stress-peening (not the combined stress-shot-peening). Finally, the mean stress sensitivity factor of M=0.5 is used to translate the curve to the constant mean stress applied during the constant mean stress – constant amplitude experimental procedure, which conforms well to both the FKM guideline and Schütz’s proposal (line 5 in figure 6).

![Figure 6: Calculated stress-life curves](image)

It should be emphasized at this point that in accordance with the FKM guideline, the resulting theoretical fatigue-life curve corresponds to a Probability of Survival P_s=97.5% and hence it should be compared to experimental curves having explicitly the same P_s as well.

It is also evident that the curve corresponding to the material’s fatigue life (for R=-1 or σ_m=0, line 4 in figure 6) can be used to create the respective curves for any mean stress desired by simply using the same mean stress sensitivity factors. This means that having the stress distribution for various variable amplitude loadings for a given geometry, one can calculate the effective mean stresses and stress amplitudes at any given point and thus calculate the corresponding anticipated damage for each load cycle D=1/N_i (where N_i is the fatigue life calculated from transforming line 4 to a new line 5 in Fig. 6, which corresponds to the calculated mean stress at the point examined and the respective stress amplitude). The damage sums for each load cycle can then be calculated using the Miner’s elementary rule at each point and plotted against the position of the aforementioned point. This way, a damage sum plot is used to visualize the fatigue life of the component (hereby a mono-leaf spring) versus a characteristic position (hereby the length). Figure 7a shows the load sequence (extracted from the spectrum of Grubisic and Fischer [6]) used to calculate the characteristic stress plots illustrated in figure.
7b (normalized to the mean stress). These plots represent the stresses obtained by FE Analysis of a given (already optimized) geometry for some of the main characteristic combination of load component values and are sequentially used to calculate the respective damage sums shown in figure 7c.
Figure 7: (a) Load sequence extracted from the spectrum after Grubisic and Fischer [6]; (b) Stress plots versus the length of the leaf for characteristic operational actions and (c) One load sequence damage sums calculated along the length of the leaf.

The damage limit line in Figure 7c represents the (normalized to itself) damage allowed for each sequence in order for the leaf spring to achieve the operational life requirement. It can be seen that the damage plot is below (around 90%) of this limit, which means that the design of this particular leaf spring is expected to present a higher operational fatigue life by around 10% compared to the requirement.

5. Experimental validation
The experimental validation consists of (a) the verification of the fundamental theoretical fatigue life curve with a set of constant mean stress, constant amplitude loading tests, and (b) the experimental determination of the operational fatigue life under variable amplitude loading. Figure 8 presents the (normalized to the mean stress) experimentally determined curve from a set of 10 specimens, along with the respective scatter-band for various probabilities of survival. As shown below, the tests (round points in Figure 8) have been performed in three different load levels and can be considered adequate for a reliable statistical analysis (at least in the finite-life region), since the conventional scatter-band produced is quite narrow ($T_{N} = N_{P_{s}=90\%}/N_{P_{s}=10\%}=1.208$).

The theoretical stress-life curve is plotted too in the above figure versus the experimental curve with a $P_{s}=97.5\%$, showing a satisfactory agreement. It is noticeable that the theoretical curve comes very close to the experimental one near the conventional fatigue limit ($N=10^{8}$ cycles), while larger deviations are observed towards the low cycle fatigue regime. Nevertheless, this approximation seems to be reliable enough to proceed with the assessment of the operational fatigue life under variable amplitude loading using directly the theoretical curve as is.

The operational fatigue life tests using the load sequence shown in Figure 7a have been conducted using the in-house built bi-axial fatigue test rig for leaf springs. An overview of this test rig is illustrated...
in figure 9. The test rig consists of a vertical actuator bringing the vertical loads and two horizontal actuators bringing the longitudinal loads (during braking actions). The test rig is built in such a way to test simultaneously two complete leaf springs and receive all original serial parts that contribute to the suspension system (original vehicle frames and peripheral eye bushings, buffers clamping devices, etc.). This way a simulation of the vehicle conditions is approached as best as possible.

![Bi-axial test rig](image)

Figure 9: Bi-axial test rig

In order for the reader to be easier acquainted with this test rig, it should be clarified that the leaf springs are assembled upside down, meaning that the road (where the loads originate from) is in the plane of the horizontal actuators, parallel to the vehicle’s frames.

The preliminary testing of only two specimens resulted to fatigue lives of 98.3% and 127.6% of the requirement respectively, which means that the theoretical calculations have the potential to successfully describe the fatigue behavior of such components.

6. Summary and Conclusions
The leaf spring production stages have been described and each expected outcome, in terms of influencing the strength and fatigue behavior, discussed in a stepwise manner. The weight of the present study has been laid upon the understanding of the material state and properties of the failure-critical tensile surfaces of leaf springs. A theoretical methodology for calculating the expected fatigue life under both constant and variable (operational) loadings has been presented, based solely on fundamental material data. The FKM guideline has been utilized along with some relatively reliable assumptions to complete the stress-life curve, along with the recommendations after Schütz regarding the mean stress sensitivity factors and the Miner’s elementary damage accumulation rule.

An optimized design of a mono-leaf spring has been used for the stress calculations through FE analysis, as well as tested in constant and variable amplitude loading. The comparison between the theoretical and experimental curves (for constant amplitude) and fatigue lives (for variable amplitude – operational loading) seems to produce a satisfactory agreement. Although these first results are encouraging, further testing (with both constant and variable amplitudes) with different leaf spring designs and materials is required to come to a safe conclusion.
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