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Coil spring failure and fatigue analysis

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ABSTRACT

This paper presents the failure and fatigue analysis results of a coil spring removed from a personal vehicle after having failed in service. Using experimental procedures like visual ob- servations, optical and scanning electron microscopy, the failed coil was examined in order to determine the causes of the fracture. Furthermore, the chemical composition of the material was determined and a hardness test performed. It was concluded that the continuous contact between the coils formed corrosion pits that served as crack initiation points leading to the final fracture. Based on these findings, the finite element model of the coil spring was built to run the stress analysis under stochastic variable dynamic loading. The quarter car model was used for the assessment of vehicle behaviour under dynamic loading. Matlab numerical routine was used to perform rainflow counting as well as Miner's cumulative damage assessment in accordance with Goodman failure criterion. The obtained results give prediction of the spring fatigue life. The results can be useful in the further design optimization of motor vehicle coil springs.

1. Introduction

Coil springs are extensively used in vehicle suspension systems and they are subjected to various dynamic loadings. Nowadays, due to continuous striving for weight reduction, the stresses caused by these loadings are significantly larger than the ones in previous generations of vehicle coil springs. Such loadings, coupled with roughness of the material surface, inclusions, deficient microstructure and harsh environmental conditions [1], can lead to failures whose causes are usually investigated experimentally [2]. However, to gain complete insight into coil spring behaviour and the possible reasons of the failure, numerical analysis is inevitable [3].

The problem of vehicle coil spring durability can be approached from different scientific perspectives. First, it is important to understand material behaviour, preferably in an investigation that includes experimentally determined fatigue behaviour of spring steels coupled with mathematical models of typical dA/dN diagrams [4]. Further, the effect of small surface scratches on coil springs produced during the manufacturing process is studied to determine fatigue strength [5]. A suitable surface treatment of coil spring steel is essential to avoid steel failures under very high cycle fatigue regime [6]. Crack initiation and growth behaviour in Si—Mn spring steel is researched to develop empirical corrosion fatigue life prediction models [7].

In order to build a model of a loaded coil spring, it is essential to understand actual loadings induced from road roughness and irregularities. Coil springs can be equipped with strain sensors during driving to accumulate fatigue strain histories that can be used in the probabilistic based analysis of automotive damage [8]. Similarly, the vibration fatigue analysis of the coil spring is performed using the results gathered under various road excitations [9]. From these signals, the power spectrum density (PSD) load profile was

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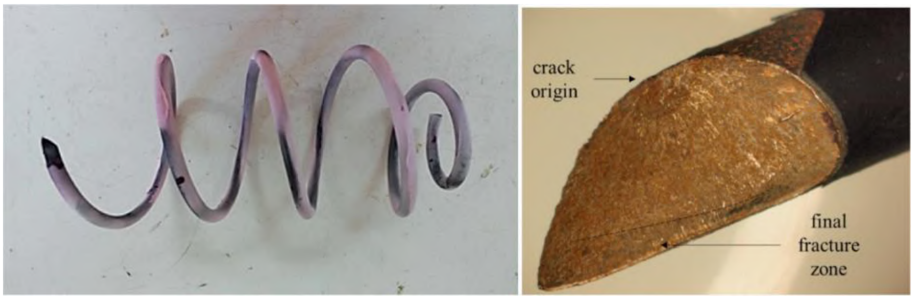

Fig. 1. a) Fractured coil spring. b) Fracture surface.

synthesized for each road type. Another approach [10] is using the neural network for road profile estimation. Generally, road profiles can be categorized as stationary Gaussian processes [11] although that is not directly applicable and narrow-band ap- proximation is proposed [12].

Once failed, coil springs are examined using experimental procedures. Insufficient shot peening and embrittlement induced from electroplating can be the cause of motorcycle spring failure [13]. Simultaneous activity of cycling loads and corrosion attack onto the material surface is also found to be the cause of motor vehicle coil spring failure [14].

In this paper, a failed coil spring has been taken from a vehicle to perform an experimental failure analysis to determine possible causes of failure and to numerically determine the fatigue life under stochastically modelled dynamic loading. The obtained results are valuable in the subsequent design improvement of coil springs.

2. Material and methods

The coil spring, Fig. 1a, mounted on a front suspension of a motor vehicle, failed after 145.000 km and 7 years of service. The spring has an overall length of 400 mm, diameter of 150 mm, pitch of 80 mm and wire diameter of 12.75 mm. The fracture occurred at the transition point from the lower bearing coil to the first upper coil, and specimens were cut in order to proceed with the experimental failure analysis.

The spring has been exposed to corrosion due to the damaged protective polymer based paint layer, probably the result of the contact between the lower bearing and the first active coil. The fracture surface is also covered in rust, Fig. 1b. Dark layer of rust can be observed in the part where the crack formed gradually and was exposed to corrosion over a longer period of time. The accelerated stage of the fracture is recognized by the light layer of rust.

Fracture surfaces of the specimens were examined using the optical and scanning electron microscope (SEM). Corrosion pits are noticed on the edge of the fracture surface where the protective paint layer was damaged, Fig. 2a. Corrosion pits formed crack initiation points that can be clearly observed in Fig. 2b) obtained by SEM under suitable magnification. Unfortunately, detailed SEM analysis under greater magnification was not possible due to the heavily corroded fracture surface.

Glow discharge spectrometer (GDS) LECO GDS500A was used to determine the chemical composition of the spring material, Table 1. The composition is adequate for the common chromium-silicon spring steel 61SiCr7 that is used in the manufacture of leaf

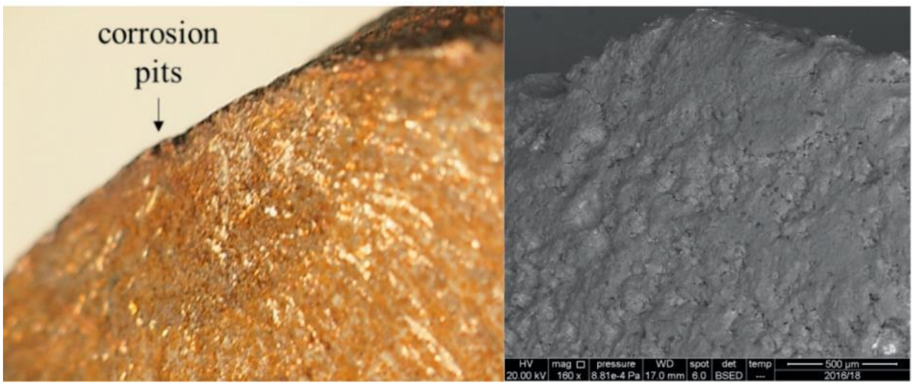

Fig. 2. Fracture surface as seen by: a) optical microscope, b) SEM.

Table 1
Chemical composition of material (w_t%).

C	Mn	Si	P	S	Mo	Ni	Cr	V	W	Cu
0.612	0.698	1.78	0.018	0.0165	0.0133	0.107	0.598	0.0139	0.0565	0.147
Al	Ti	Co	Nb	Pb	Sn	As	Sb	Zr	Rest	–
0.0036	0.0134	0.0497	0.0704	0.0029	0.146	0.0213	0,003	0.0087	95.6	–

springs and coil springs for light and heavy vehicles.

Hardness of material, tested by Struers hardness tester Duramin-2, was found to be 590 HV (Vickers hardness number).Ultimate tensile strength derived from the hardness value [15] is σ_{UTS} = 3.2 HV = 1888 MPa.

3. Calculation

The finite element (FE) model of the considered coil spring was built in order to perform the numerical analysis of the stresses and fatigue life. Dimensions of the actual coil spring were used to build 3D FE model of quadratic tetrahedron elements in Ansys.

In order to verify the FE model, first a simple static stress analysis is performed in order to compare numerically and analytically obtained results. The spring was loaded with 4000 N, an equivalent of the quarter car weight with the passengers included. The maximum shear stress obtained numerically is 806 MPa, Fig. 3.

The analytically calculated shear stress is:

$$\tau_{max} = K_c \frac{8FD}{\pi d^3} = 787.35 \text{ MPa}. \tag{1}$$

Here, K_c is the correction factor calculated regarding the spring diameter and the wire diameter ratio, D/d. The results differ by no more than 2.5% giving confidence to the further use of the FE model.

The stress intensity factor K_{III} is assessed numerically, inserting a semi elliptical crack at the node with the maximal shear stress, Fig. 4, and the obtained value is 1060.7 MPa $\cdot$mm$^{0.5}$. The size of crack is determined based on experimental observations given in Section 2 of the paper where the dark area represents the size of crack inserted into the 3D model. The critical K_{IIIC} for spring steel is 1012 MPa $\cdot$mm$^{0.5}$ [16], therefore, a crack propagation is to be expected, initially by fracture Mode III and afterwards by fracture Mode I.

In order to perform a thorough fatigue analysis of the coil spring, material fatigue behaviour had to be modelled according to the experimental data [17]: ultimate tensile strength σ_{UTS} = 1850 MPa, yield strength σ_{YS} = 1610 MPa, ultimate shear stress τ_{UTS} = 0.67$\cdot\sigma_{UTS}$ = 1239.5 MPa, yield shear stress τ_{YS} = 0.577$\cdot\sigma_{YS}$ = 928.97 MPa, torsional endurance limit τ_e = 470.8 MPa. Fig. 5 presents the $S-N$ diagram for 61SiCr7 12.5 mm diameter wire for fully reversed torsion.

Also, loads have to be correctly modelled in order to properly analyse fatigue. There are two basic methods for the load analysis in the fatigue study: amplitude (time) and frequency based methods [18]. Amplitude (time) based method uses rainflow cycle counting for extracting hysteresis loops in the load signal and it is the most widely used method for evaluating fatigue damage. The aim of frequency based methods such as the extreme response spectrum (ERS), i.e. the frequency damage spectrum (FDS) proposed by [19], is to analyse the response of the system (mechanical part) as a function of its eigen frequency, so the damage turns out to be a function

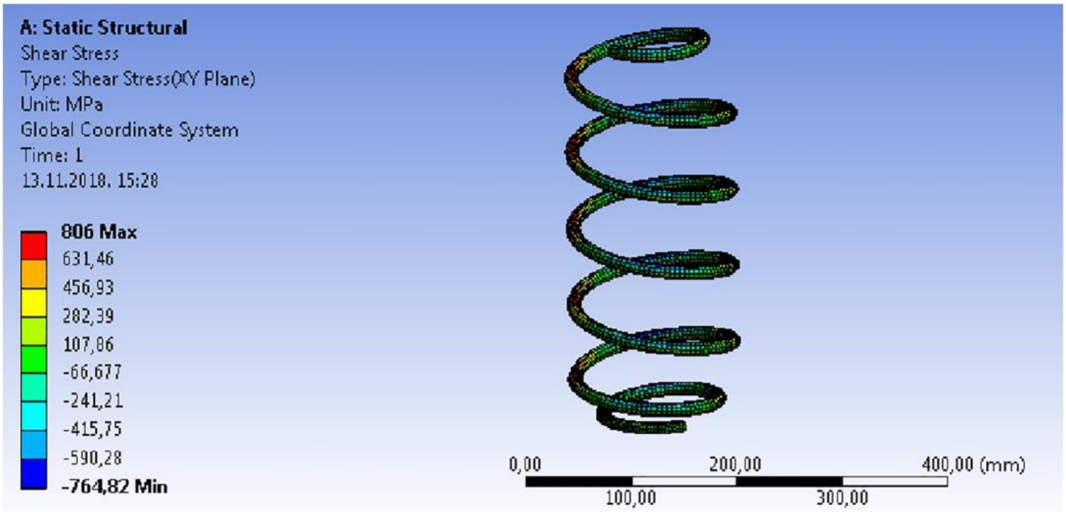

Fig. 3. FE model of coil spring with shear stress analysis results.

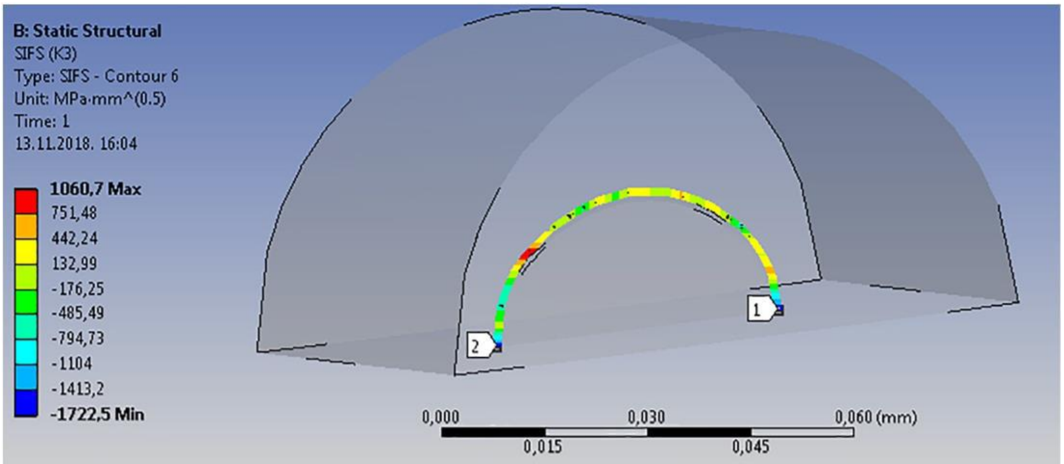

Fig. 4. FE assessment of K_{III} stress intensity factor.

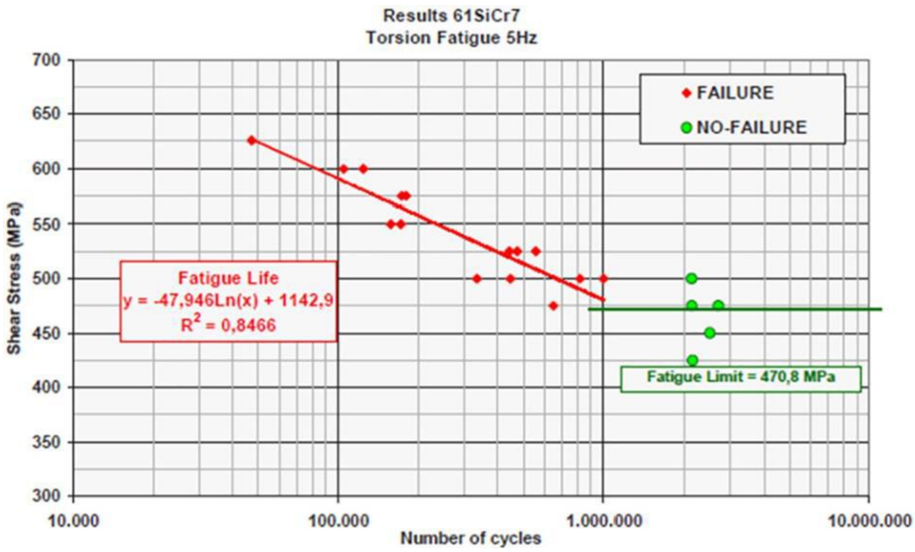

Fig. 5. S—N diagram for fully reversed torsion R = -1, spring steel 61SiCr7 [17].

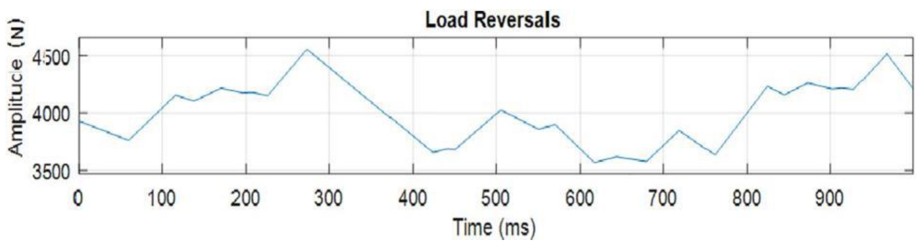

Fig. 6. Dynamical loading on the coil spring.

of frequency [20].

According to ISO 8608 [21] standard road profiles are classified from very good (A-B class, with max. profile height ± 15 mm), to good (B—C class, with max. profile height ± 25 mm), average (C-D class, with max. profile height ± 50 mm), poor (D-E class, with max. profile height ± 100 mm) and very bad (H class, with max. profile height more than ± 100 mm). Road profile in the same standard is described by the function of the power spectral density (PSD):

$$G_d(\Omega) = G_d(\Omega_0)\cdot\left(\frac{\Omega}{\Omega_0}\right)^{-2} \tag{2}$$

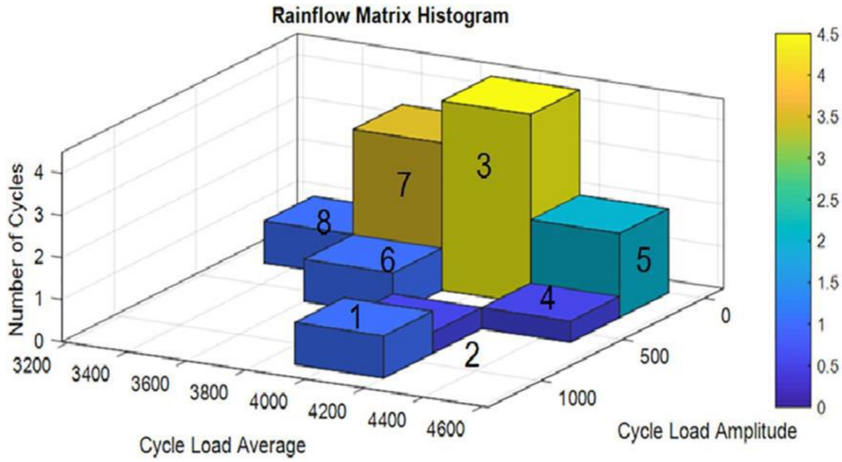

Fig. 7. Rainflow counting histogram.

Table 2
Midrange loads, load amplitudes, number of cycles for every bin.

Load no.(bin)	1	2	3	4	5	6	7	8
Midrange load, F_m [N]	4050	4050	4050	4350	4350	3750	3750	3450
Load amplitude, F_a [N]	1050	750	150	450	150	450	150	150
Number of cycles, N	1	0.5	4.5	0.5	2	1	3.5	1

where $\Omega = 2\pi/L$ is the angular frequency of the longitudinal road profile, L is the road roughness wavelength, Ω_0 is the reference angular frequency, $G_d(\Omega_0)$ is the road roughness indicator, defining the general road surface condition in accordance with classification. Random road profile is approximated by the superposition of N sine waves:

$$h(s) = \sum_{i=1}^{N} A_i \sin(\Omega_i s - \Psi_i) \quad (3)$$

where s is the momentary position (depends on the speed of the vehicle), Ω_i is the angular frequency of the i-th sine wave, the Ψ_i is the random generated phase angle of the i-th sine wave, A_i represent amplitudes.

Based on the conducted experimental analysis of the failed coil spring, it can be noticed that the fracture surface is oriented at 45° to the wire centerline, typical of torsional fatigue failure under cyclic loading, Fig. 2. The fracture started from corrosion pits formed on the surface of the wire due to the protective paint layer damaged by the contact between two adjacent coils. Radiating ridges on the fracture surface, Fig. 3, spreading from pits also indicate fatigue failure. At the opposite side of pits, the final stage of the fracture can be recognized where the remaining ligament broke and split the wire into two pieces.

4. Conclusion

This paper presents a research on the causes of vehicle coil spring failure. Using experimental methods (visual observations, chemical composition analysis, hardness testing, optical and SEM analysis), the fractured spring was examined, and from the results it can be concluded that this is an example of corrosion fatigue failure.

To further enhance the knowledge about the fatigue limits of vehicle coil springs, a numerical analysis was performed. Loading was modelled stochastically considering poor road surface conditions. The obtained results give an estimation of the spring's fatigue life when exposed to actual loadings coming from the road surface.

The results are useful in understanding the mechanics of the coil spring in the vehicle suspension system and the further design improvement regarding failures reduction. A further analysis could also include some probabilistic estimation method. In addition, research could be expanded involving other types of vehicle coil springs and/or other spring material. However, that direction of research heavily relies on the availably of additional failed coil spring that could be extracted from vehicles.

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