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EXPERIMENTAL AND NUMERICAL ANALYSIS OF A HELICAL SPRING FAILURE

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Abstract. Results of experimental and numerical analysis of a broken motor vehicle helical spring are presented in this paper. Location of the fracture is on a first active coil of the spring. Experimental part of the research employed optical microscopy that revealed fractured surface microstructure and allowed for detection of inclusions. Corroded fracture surface limited scanning electron microscopy examination (SEM). Nevertheless, corrosion pits on the edge of the spring wire which served as crack initiation points could be detected by SEM along with radiating ridges left by the fracture front that propagated to the opposite edge of the wire. Optical emission spectrometer with glow discharge source sample stimulation was used to determine material chemical composition that is adequate to spring steel 61SiCr7. Additionally, hardness test was performed and obtained value was used to derive maximum tensile strength of the steel. Experimentally collected data served as input for numerical analysis of helical spring. Finite element analysis of a helical spring model was performed. Stress distribution was determined and fatigue life of the undamaged helical spring predicted. Results were compared with those obtained analytical. Causes of failure are outlined assessing the results of the performed experimental and numerical analysis. Insufficient corrosion protection and excessive contact between the coils caused damage that developed from initial crack to final fracture of the spring. Results obtained by this research are valuable in understanding fracture behavior of helical spring mounted in suspension system of various motor vehicles. Given the presented results, further improvements of spring design can be made in order to reduce failures.

1 INTRODUCTION

Helical springs are used in the construction of motor vehicles suspension system as one of the primary elastic members connecting the wheel and the vehicle chassis. Absorption and subsequent release of external loads from uneven road surfaces comes in a form of elastic energy so, if designed properly, springs tend to return to their initial form when unloaded.

To assure proper design, engineers can, among others, benefit from failure analysis of broken springs. Springs fail mostly because of the local stress raisers that come in a form of a material surface roughness, inclusions and deficient microstructure. Causes of common spring failures along with spring material characteristics, manufacturing of springs and their fundamental stress distribution are outlined in the work of Prawoto et al. [1]. Dealing with the failure of motor vehicle coil springs, some of the recent work includes failure analysis of shock absorption helical spring in a motorcycle [2] where insufficient shot peening and embrittlement induced from electroplating were recognized and, based on this, a process optimization was proposed to reach the standard service life. Experimental investigation of a prematurely failed passenger car coil spring discovered that it was caused by inherent material defects coupled with deficient processing [3]. Experimental procedures employed on a fractured torsion springs mounted on an electric-powered vehicle determined that the fractures initiated due to electric arc damage [4]. Besides experimental failure analysis, numerical approach is also employed to gain thorough insight into the mechanical behaviour of failed component. Stress analysis, fatigue life calculations and failure simulations are fairly easy performed using finite element analysis [5]. Causes of compression helical spring fracture were analysed by employing experimental methods while numerical methods served to determine contact points between the spring coils from which crack originated [6].

Additionally, it is also important to understand the behaviour of spring material in order to improve performance of springs. Some of the recent work on this topic includes a comprehensive overview of fatigue behaviour of spring steels DIN 17223C and 55Si7 coupled with mathematical models of adequate da/dN diagrams [7]. Ductility of Si-Cr spring steel is improved by refining grain boundary carbides using thermomechanical treatment [8]. Empirical corrosion fatigue life prediction models are developed based on a study of a crack initiation and growth behaviour in Si-Mn spring steel [9]. Basic spring material behaviour can be significantly improved by treatments like heating, quenching and tempering [10]. Also, microshot peening can be successfully employed to improve fatigue life of spring steel [11]. Proper surface treatment of coil spring steels needs to be employed in order to avoid surface defects that can become predominant origin of spring steel failures under very high cycle fatigue [12].

Research of springs is ongoing as new design and spring materials coupled with harsh service conditions give reason for continuous improvement. Failure analysis of fractured springs serves as a valuable tool for design improvement. This paper presents results of experimental and numerical analysis of a broken motor vehicle helical spring. Results can be taken as a reference in further improvement of helical springs, especially having in mind that local car dealership confirmed that there has been a noticeable amount of failures on that particular spring design.

2 EXPERIMENTAL ANALYSIS

2.1 Visual and microscope examination

Helical spring mounted on a front suspension of a passenger car fractured after 145.000 km and 7 years of service. Fracture occurred at the transition point from the lower bearing coil to the first upper coil. Geometry and dimensions of helical spring extracted from the car are shown in Fig. 1.

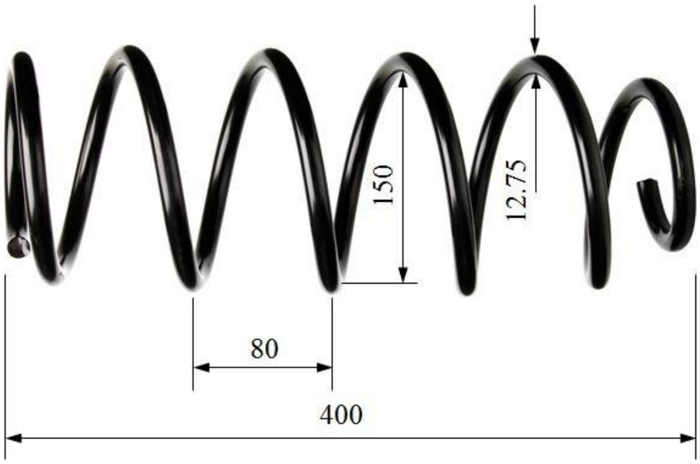

Figure 1: Helical spring dimensions (in mm)

In order to perform experimental analysis, specimens were cut from fractured helical spring, Fig. 2. Fracture surface is oriented at 45º to the wire centerline which is typical for torsional fatigue failure under cyclic loading. Protective layer of polymer-based paint is damaged around the fracture surface. Damage can be contributed to the contact of bearing and first active coil.

Figure 2: Specimens extracted from failed coil spring

Heavily corroded outer surface of the wire is exposed in Fig. 3 and there is a layer of rust on the fracture surface, also, Fig 4. Thicker and darker semicircular part of the rust layer marks portion of the surface where crack formed gradually and was exposed to corrosive environment for a longer period of time before the final failure occured. Rest of the fracture surface is covered in lighter layer of rust and marks a portion of surface where accelerated crack propagation happened.

Figure 3: Heavily corroded wire surface

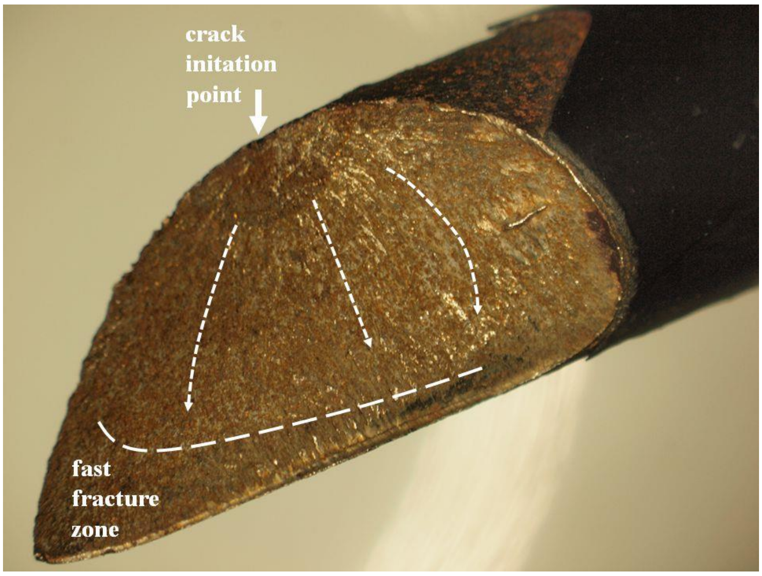

Figure 4: Fracture surface

Corrosion pits can be observed at the point where the protective layer of paint was damaged. Fracture originated from one of this pits and continued propagation towards opposite end leaving radiating ridges behind and suggesting fatigue failure caused by cyclic loading from the vehicle. At the side opposite of the crack initiation point, fast fracture area can be observed corresponding to the final stage of failure.

Specimens of a failed helical spring were examined using optical and scanning electron microscope. Optical microscopy was performed using Olympus SZX10 stereo microscope and investigation of the fracture surface was concentrated on the area of probable crack initiation point, Fig. 5.

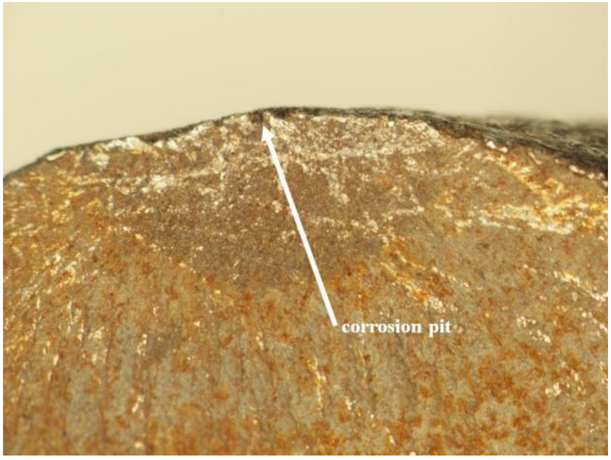

Figure 5: Corrosion pit serving as crack initiation point

Corrosion pits can be observed at the edge of the fracture surface where the protective paint layer is damaged. Main pit served as crack initiation point from which crack propagated towards opposite edge of the wire causing final failure.

Crack initiation area, obtained by FEI Quanta 250 scanning electron microscope (SEM) under suitable magnification, is shown in Fig. 6.

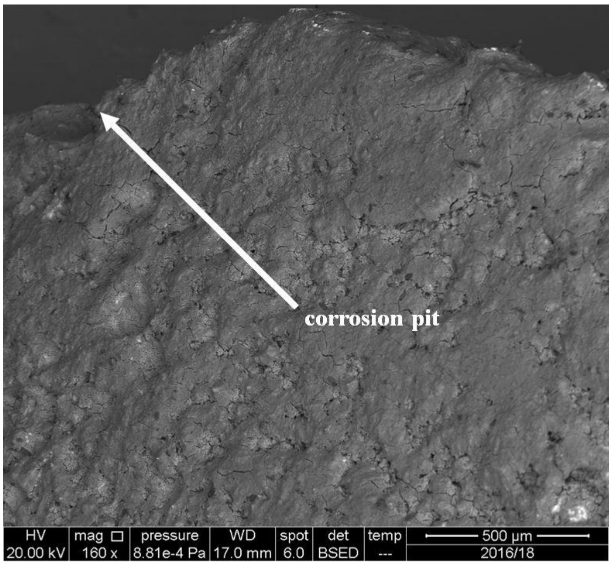

Figure 6: SEM magnification of crack initiation point at corrosion pit

SEM analysis was difficult to perform because the fracture surface was damaged by corrosion. Examination of the fracture surface at 80x magnification revealed a heavily oxidized and corroded surface which obscured fracture surface details. Although an attempt was made to remove the corrosion layer using aggressive cleaning agent, corrosion products could still be seen on SEM images.

2.2 Material

Glow discharge spectrometer (GDS) LECO GDS500A was used to determine chemical composition of spring material, Tab. 1.

Table 1: Chemical composition of spring material (wt%).

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	

Comparing it to standard materials used in spring manufacturing, composition is adequate to chromium-silicon steel 61SiCr7. This spring steel is typically used in production of light and heavy motor vehicle leaf springs and coil springs, safety valve springs, shock absorbers, instrument springs, friction plates, etc. If compared to EN 10089-2002 standard, percentage of manganese in tested steel is just below the standard range (0.7-1 %), while chromium exceeds the maximum standard value (0.2-0.45 %). Standard maximum tensile strength of steel 61SiCr7 is 1850 MPa.

Using Struers hardness tester Duramin-2 hardness test was performed. Mean hardness value is 590 HV (Vickers hardness number) and it can be used to derive maximum tensile strength of the tested material [13]:

$$\sigma_{TS} = 3.2HV = 1888 \text{ MPa}. \tag{1}$$

3 NUMERICAL ANALYSIS

Common failure analysis usually constitutes only of experimental metallurgical analysis in order to establish the causes of failure. Since the failed structures are often subjected to tensile overload, excessive creep or localized fatigue damage, mechanics of the failure should also be considered, e.g. stress analyses, fatigue life analyses and simulations of failure process. Finite element (FE) analysis represents cost and time effective tool for determining the causes of failure and this numerically obtained results complement the ones obtained experimentally providing broader insight into the failure of structures.

According to geometry in Fig. 1, simplified 3D FE model of helical spring was built in Ansys. A model without any crack was analyzed first, in order to determine stress range, contact point between the coils and fatigue life of undamaged spring. A load of 4000 N was applied on top coil and nodes on bottom coil were restrained from motion. Load was estimated as a quarter of total car weight plus average passenger weight. Material behavior was modelled according to available experimental data for 61SiCr7 spring steel [14]. In accordance with the previously derived value of maximum tensile strength, data for 61SiCr7 spring steel annealed at 425ºC were taken along with results of fatigue tests and S-N curves needed for proper numerical model.

Shear stress distribution in the considered helical spring is presented in Fig. 7.

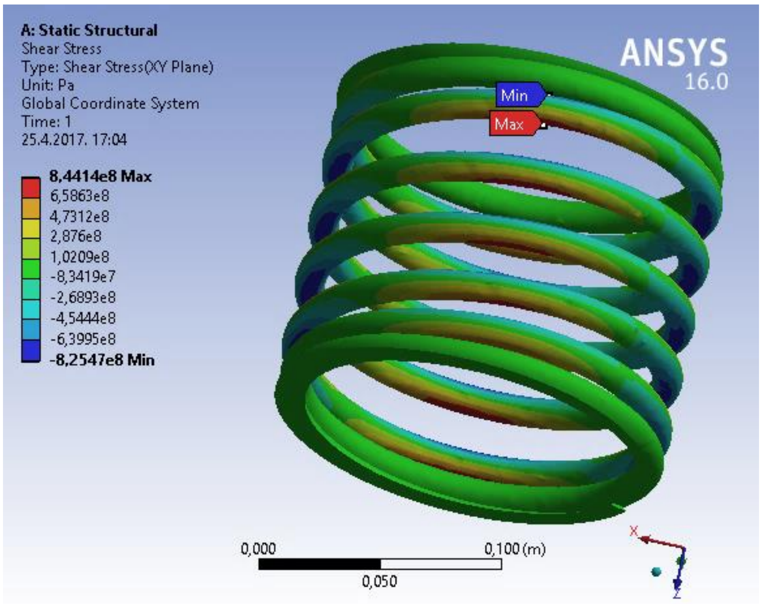

Figure 7: Shear stress distribution

It can be noted that the maximum value of stress is numerically predicted just at the point where actual fracture occurred. During service, dynamic loads and shocks resulted in contact between the bearing coil and the first active coil. As a result of repeated contact and impact between the coils, the contact surfaces were gradually worn out leading to crack occurrence and fracture. FE model was built to simulate frictionless contact behavior between the mentioned coils.

In order to validate FE model, numerically obtained values of shear are compared to ones calculated analytically. The maximum stress in the spring wire, occurring on the inner surface, can be calculated as [15]:

$$\tau_{\max} = K_W \frac{8FD}{\pi d^3}, \tag{2}$$

where F is the load, D outer diameter of the spring, d wire diameter and K_W is a Wahl's coefficient:

$$K_W = \frac{4C-1}{4C-4} + \frac{0.615}{C}, \tag{3}$$

while C is a spring index:

$$C = \frac{D}{d}. \tag{4}$$

According to Eq. 2, maximum shear stress in considered helical spring is 827.4 MPa which can be correlated to 844.1 MPa obtained numerically.

Also, in order to numerically predict fatigue life of helical spring, fatigue analysis is performed and results are presented in Fig. 8.

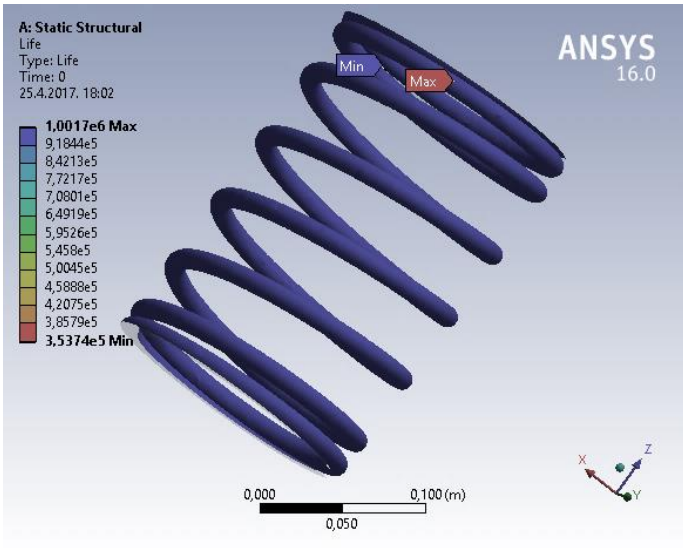

Figure 8: Fatigue life

In order to get more accurate results, loads coming from road irregularities are considered, also. Passing of the vehicle on irregular road surfaces generates oscillation of the vehicle mass with a consequent increase of the load. Final load is a combination of several factors, e.g. vehicle mass, travelling speed, type of suspension, road irregularities, etc. Quarter car model (QCM) [16] can be used to study the interaction between vehicle and road profile. Also, classification of road profiles according to ISO 8608 [17] has to be considered. The use of ISO 8608 presumes that a specific road has equal statistical properties along an examined section. In this work, ISO A-B road profile was chosen along with 70 km/h vehicle speed. A Matlab code was written [18] to calculate the behavior of a vehicle according to road irregularities and further to estimate the effect on helical spring fatigue life. Fig. 9 shows non-constant amplitude load used in the analysis.

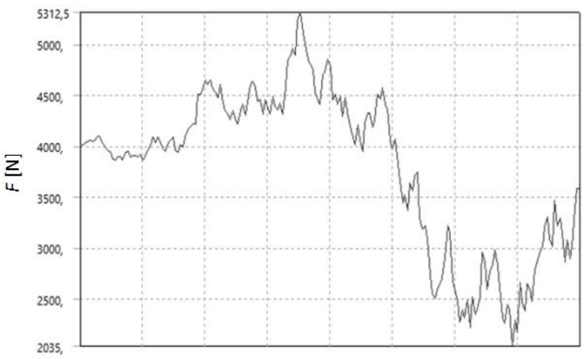

Figure 9: Non-constant amplitude load

Fig. 10 has shear stress distribution in the considered helical spring with load from road irregularities added and Fig. 11 predicted fatigue life.

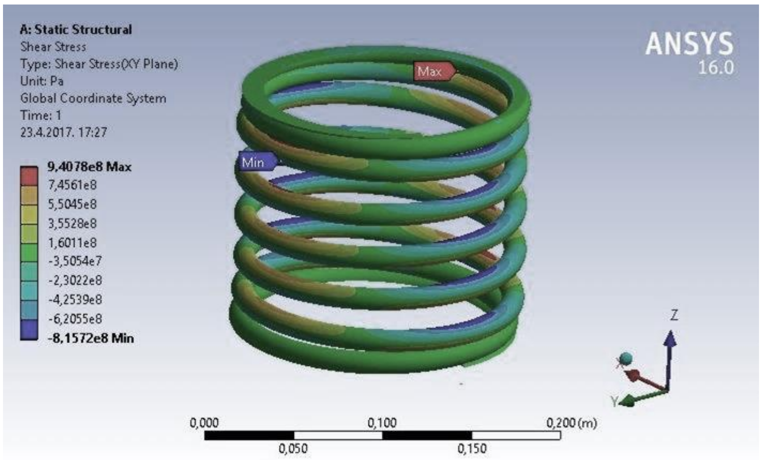

Figure 10: Shear stress distribution with road irregularities load accounted

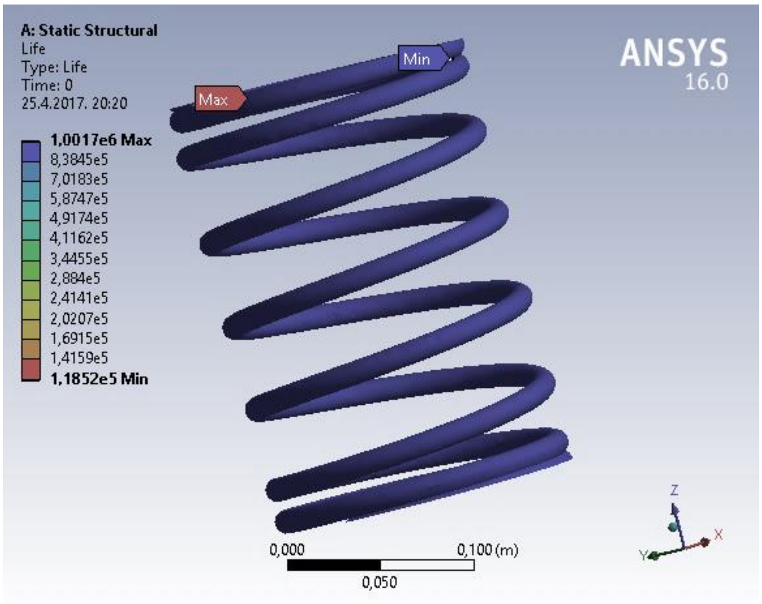

Figure 11: Fatigue life with road irregularities load accounted

5 DISCUSSION

Visual examination of failed helical spring revealed that the protective layer of paint was mechanically damaged at the contact point between the lower bearing coil and first adjacent active coil. Therefore, wire surface was exposed to corrosive environment allowing the formation of corrosion pits. These pits served as crack initiation points influenced by cyclic loading from the vehicle travelling on the road irregularities. Primary fracture zone that was exposed to corrosion for a longer period of time can be observed on the fracture surface. Crack front propagated towards opposite edge of the wire leaving radiating ridges behind. Finally, fast fracture zone can be observed near the opposite edge of the spring wire, marking the final stage of failure.

Experimental analysis revealed that spring was made of 61SiCr7, a spring steel with somewhat elevated content of silicone and chromium. Chromium at steels tends to increase tensile strength, hardness, toughness, resistance to wear and corrosion [19], while silicon is used as a deoxidizer in the manufacture of steel and it slightly increases tensile strength and can help in increasing the toughness and hardness levels. However, special attention must be taken to ensure that paint layer remains undamaged in order to protect spring against exposure to corrosive environment.

Optical and scanning electron microscopy examination revealed damage to the wire surface caused by continuous contact between the coils. Heavily oxidized and corroded fracture surface limited SEM examination so deeper insight could not be performed.

Performed finite element analysis served to determine stress distribution along the spring, contact point between the coils and fatigue life of undamaged spring. Comparing results of numerically predicted and analytically calculated maximum stress level, it can be noted that FE model successfully represents real helical spring. In order to obtain accurate fatigue life, load on helical spring is modelled first just as a quarter of average vehicle weight, then additionally with load from road irregularities. Difference in fatigue is significant suggesting that load from road irregularities should also be included in vehicle helical spring calculation.

6 CONCLUSION

Results of the research presented in this paper gave insight into the causes of motor vehicle helical spring failure. Failed spring was examined experimentally; visual observation, determination of chemical composition, hardness testing, optical and scanning electron microscope analysis were employed. Additionally, FE analysis was performed to determine stress ranges, contact points between the coils and fatigue life.

Experimental results suggest a corrosion fatigue failure. Protective layer of paint was damaged which introduced corrosion pits on the surface of the wire. Corrosion pits served as crack initiation points that grew under the influence of cycling loading causing the final fracture. Radiating ridges on the fracture surface show the path of crack advancement.

Finite element analysis was employed to determine stress levels in helical coil spring along with numerical estimation of fatigue life. Obtained results are valuable in understanding fracture behavior of helical spring as a part of motor vehicle suspension system. Further improvements of spring design are possible in order to reduce potential failures.

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