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Lidia Bohun [1], Eduard Pleshakov [2], Sergiy Shvachko [3]

1. Department of Applied Materials Science and Materials Engineering, Lviv Polytechnic National University, Ukraine, Lviv, S. Bandery Street 12, E-mail: lidabohun@gmail.com, ORCID 0000-0002-3077-7756
2. Department of Applied Materials Science and Materials Engineering, Lviv Polytechnic National University, Ukraine, Lviv, S. Bandery Street 12, E-mail: ed.matchak@gmail.com, ORCID 0000-0002-2229-2820
3. Department of Applied Materials Science and Materials Engineering, Lviv Polytechnic National University, Ukraine, Lviv, S. Bandery Street 12, E-mail: shvsg0984903405@gmail.com, ORCID 0000-0003-2825-9519

FAILURE ANALYSIS OF A MOTOR VEHICLE SUSPENSION HELICAL SPRING

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Abstract. The purpose of this work is to reveal the cause of the failure of the motor vehicle rear suspension barrel-shaped spring with the progressive elasticity characteristic and predict measures to increase the lifetime of springs of this type. The fracture of the spring occurred on the middle coil, which operates under conditions of more severe stress in comparison with other coils. The chemical composition of the spring material, determined by X-ray fluorescence spectral and microstructural analyzes, corresponded to chromium-silicon steel 54SiCr6. In terms of structure and mechanical properties, the spring material met the standards. No traces of decarburization were detected, and no crack initiation, caused by non-metallic inclusions, was found in the material of the fractured spring. Macroscopic examination of the spring surface did not reveal any cracks, scratches, dents, traces of blows with stones and marks of spring coiling tool. Instead, extensive areas of exfoliation of the protective coating were found. The metallographic analysis revealed selective corrosion in the form of pitting damage in places of exfoliation of the protective coating. The fatigue crack propagates from the certain deep pit with the reorientation of the crack plane along the spiral surface to the central axis of the coil wire. After depletion of the safety margin, the spring broke down quickly. The fast fracture zone contains steps of the river pattern formed due to the spiral reorientation of the fracture surface. The research can be used to understand the importance of adhesive strength and wear resistance of protective coatings on the spring surface. Their local exfoliation causes subsequent corrosion damage to the spring, which stimulates its fatigue fracture.

Keywords: barrel-shaped spring, spring steel, fracture, microstructure analysis, failure analysis, corrosion fatigue.

Introduction and problem statement

Automation and robotization of industrial and technological processes in different branches of human activity is a leading and long-term trend of development of modern society [1]. Nowadays, industrial robots have become quite widespread and have formed the main technological base of the machine-building, instrument-making, electrical and electronic fields of the world's industry [1], [2].

The suspension system is one of the vital components of the car, which guarantees traffic safety. Important elements of the suspension are springs and shock absorbers which absorb the energy of blows from roughness of a road surface, provide safe and comfortable driving of passengers without noise, blows, vibrations, increase lifetime of other systems of the car. The suspension springs hold the weight of the car while maintaining the required ground clearance, provide a reliable grip of the tires on the road.

The implementation of a constant trend in the modern automotive industry – reducing the weight of cars – also applies to steel suspension springs. Reducing their weight requires the use of steels with greater strength, elasticity, and relaxation resistance. However, increasing the strength of steel reduces its margin of ductility, which must be offset by the higher quality metallurgical production and technological processing of steel.

Analysis of modern information sources on the theme of the paper

Ensuring the reliable and safe operation of vehicles requires constant improvement of suspension systems, materials, etc. To do this, a lot of research work is being done in various directions, in particular, to determine the influence of various factors on the damageability of the suspension springs.

Loss of spring stiffness causes their subsidence, which increases vibration, shaking, body skew, reduces ground clearance, and damages the surface layer of coils due to the formation of traces and recesses from mutual impacts of adjacent coils [1]. This can have accidental consequences. In the work [2], the factors influencing the loss of spring stiffness and their subsidence are considered.

Paper of Prawoto et al. [3] fundamentally analyzes the stress distribution in the suspension springs, the characteristics of elastic materials, and the technology of manufacturing springs. Premature failure of the suspension springs is caused by metallurgical and technological defects (non-metallic inclusions, decarburization of steel, etc.), defects of the spring surface that create stress concentration, weakening of the cross-section of the springs due to corrosion. Studies [4] confirm that metallurgical factors, such as non-metallic inclusions, decarburization, internal cracks, cavities, corrosion are the main factors of premature failure of the suspension components.

Corrosion is a common cause of suspension springs degradation. It causes a weakening of their mechanical properties and a decrease in the ultimate life [5]. Corrosive damage caused by the external environment begins on the surface of the springs and, spreading over time, can be the root cause of fatigue fracture.

The nucleation of fatigue cracks begins on the surface of the springs in weakened areas or places of stress concentration. An important role is also played by the stress state of the surface layer: the residual compressive stresses counteract the nucleation and growth of fatigue cracks and, conversely, tensile stresses, arising, for example, due to decarburization, stimulate the development of fatigue. In particular, the influence of residual stresses on the resistance of steels to corrosion failure is considered in the work [6]. To increase the fatigue life of steel springs, Harada et al. [7] recommend microshot peening, which generates favorable compressive stresses in the surface layers of the springs.

The authors of the study [8], based on the failure analysis of the tension spring, recommend stress relieving operations, reducing surface irregularities, such as pits and cracks.

It is noted [9], [10], [11] that helical coil springs are more often fractured in the zone of transition from the reference to the first active coil for various reasons, in particular, due to the collection of a corrosive environment in a narrow space between the adjacent coils [11].

A number of researchers [11], [12] found that the fracture of the springs with a protective coating investigated by them occurred due to corrosion fatigue. The places of the nucleation of fatigue cracks were the areas of fracture of the polymer-based paint layer under the influence of impact closure of adjacent coils. Unprotected areas were damaged by pitting corrosion, and the fatigue fracture of the spring started from them.

Fragoudakis et al. [13] on the example of the 56SiCr7 spring steel demonstrate a significant increase in the lifetime of springs by optimal heat treatment.

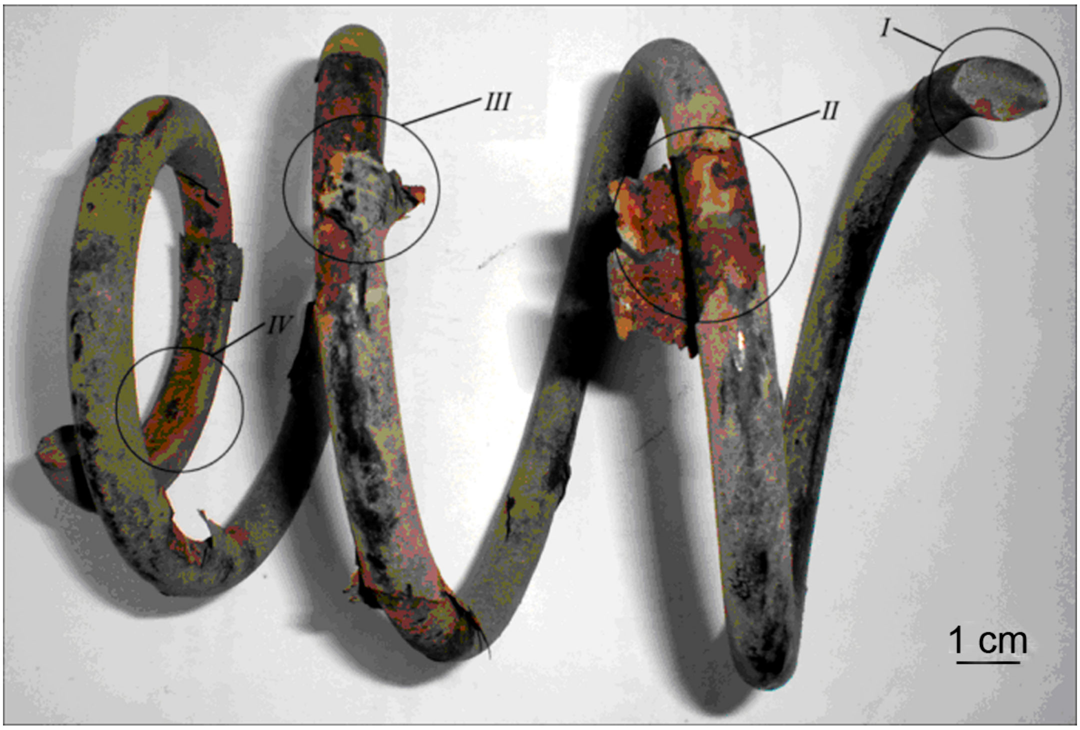
Aim and task of the investigation

Investigation and analysis of the causes of failure of the safety-critical springs of the vehicle suspension do not stop due to the continuous renewal of spring designs, improvement of spring materials, and changes in operating conditions. This requires further analysis of various cases of a spring failure, which can be used by manufacturers to develop measures to improve their quality and reliability. Therefore, the purpose of this work is to reveal the cause of the failure of the coiled helical spring of the rear suspension of the Ford Fiesta car and predict measures to increase the lifetime of springs of this type. This spring belongs to the group of springs with progressive elasticity characteristics: it is barrel-shaped and has a longitudinal variable pitch. In a static condition of the car suspension, all coils of the spring are loaded and provide the certain stiffness of the spring. As the load increases, the coils with a smaller step close, the number of active coils decreases, and the spring stiffness increases. Coiled springs of suspensions are springs of repeated dynamic action and are intended for holding axial compressive cyclic loadings [14].

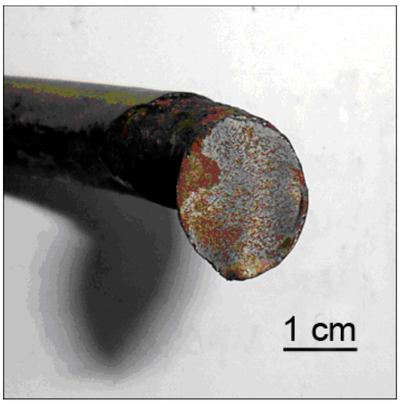
The investigated spring of the rear suspension had fractured after 210 thousand km of run of the car.

Experimental procedure and results

The fractured spring has the form of a barrel-shaped helix coiled to the right (Fig. 1, a). The outside maximum diameter of the spring is 108 mm, the minimum diameter is 76 mm, the total height of the unloaded spring is 336 mm. The total number of spring coils is 7 and the spring wire diameter is 10 mm. The spring weight is 1.25 kg. The fracture of the spring occurred on the middle coil having the largest diameter.



a



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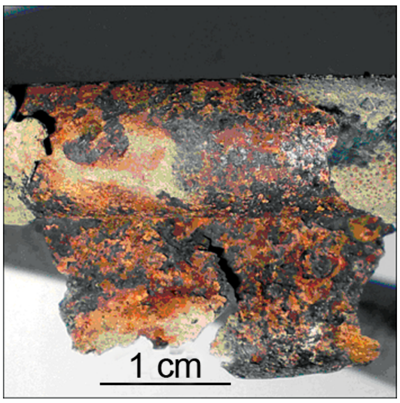

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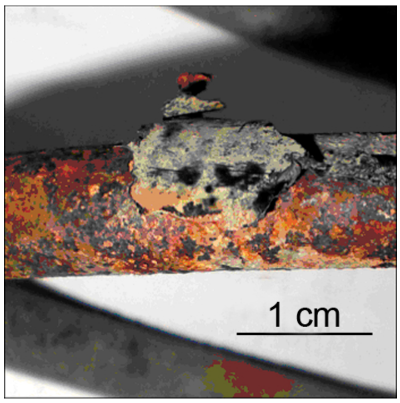


d

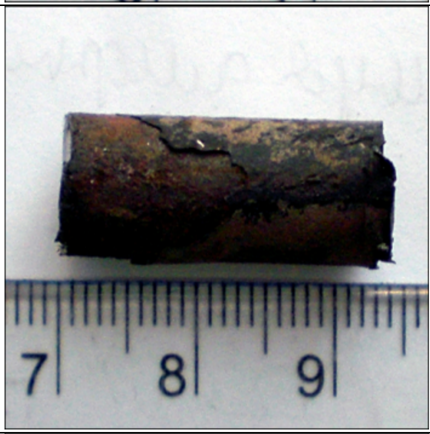
Fig. 1. The appearance of the spring of the rear suspension of the Ford Fiesta car: a – general view; b – fragment I; c – fragment II; d – fragment III

The quality of the spring was checked visually with a magnifying glass with 5 times magnification in accordance with DSTU 8429:2015 [15]. The appearance of the spring and the fracture was documented using a Casio Exilim 8.1 Mega Pixels camera (Fig. 1, *a*, *b*). During the inspection, no cracks, hairlines, rolled-in scales, electric burns, small dents, scratches, marks of spring coiling tool, and the remains of lubricants were observed on the surface of the spring. Instead, traces of rust and erosion of the protective coating were observed, which led to its exfoliation from the spring surface (Fig. 1, *c*, *d*).

For the subsequent researches, three samples of 20–30 mm in length were taken from places of the main damages (Table 1). Samples were cut off with acceptable heating of steel, which did not cause structural changes in it.

Table 1

Protocol for sampling and marking of samples for investigation

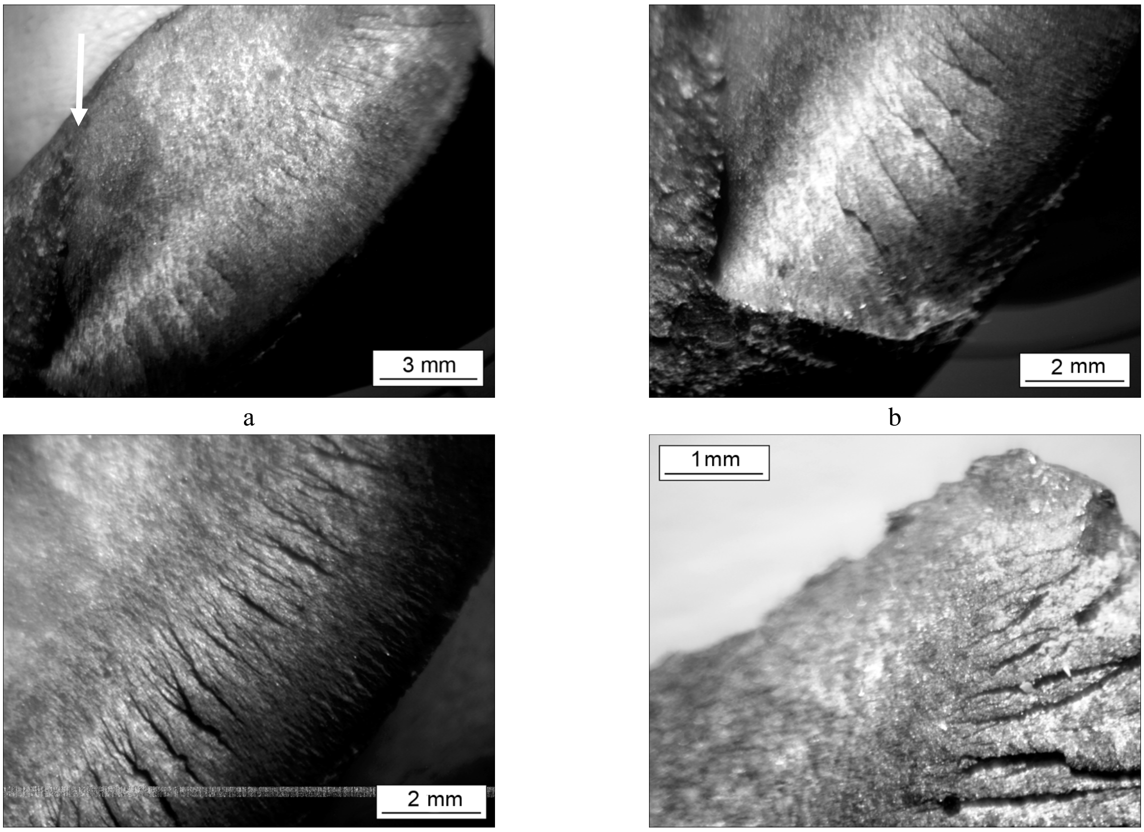
Sample		Marking of samples	Type of study
No. of sample	general view		
1		1	- macrofractographic (MBS-9 microscope); OM; ×1…×7
2		2	- microstructural in the state after operation: • general microstructure; • non-metallic inclusions; • the depth of the decarburized layer; • defects; - determination of the chemical composition of the steel: X-ray fluorescence analysis (ElvaX)
3		3	- microstructural after annealing to determine the carbon content in the steel

Macrofractographic studies of the fracture surface were performed using an MBS-9 microscope at magnifications of up to 7 times. The fatigue crack propagates from the fracture origin (Fig. 2, *a*, indicated by an arrow) with the reorientation of the crack plane along the spiral surface to the central axis of the coil wire (see Table 1, sample 1). The zone of the steady fatigue crack propagation is smoothed and identified by fatigue ridges – traces of movement of the crack front, which diverge concentrically from the crack initiation point (Fig. 2, *a*, *b*). After depletion of the safety margin, the spring broke down quickly. The fast fracture zone with a transverse size of about 6 mm contains steps of the river pattern formed due to the spiral reorientation of the fracture surface (Fig. 2, *c*, *d*).

Microstructural studies (DSTU ISO 4967:2017) were performed on non-etched and etched with 4% nitric acid solution microsections using an MMT-14C optical microscope at magnifications of 100 to 500 times.

Evaluation of non-metallic inclusions in steel springs was performed according to DSTU ISO 4967:2017 (GOST 1778) [16]. A small number of dot particles of oxides (Fig. 3) and single elongated sulfides, which are usually double sulfides of iron and manganese, were found. Oxide and sulfide inclusions in their maximum size are twice smaller than the inclusions that correspond to the grade 1 of the reference scales, so they are evaluated by the grade 0.

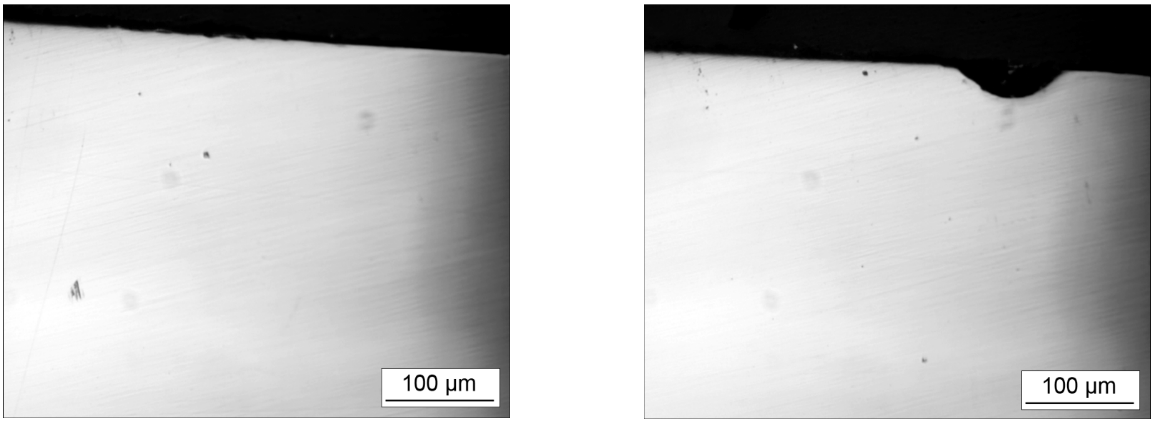
Car springs are made of rolled products, for which dot inhomogeneity, central porosity, and liquation square should not exceed the grade 2 [15]. Therefore, the quality of spring rolling on non-metallic inclusions meets the requirements for the rolling for the manufacture of car springs.



c d

Fig. 2. Macrostructures of the zones of the spring fracture surface: (a) the crack origin (indicated by an arrow); (b) transition from the fracture origin to the fatigue crack propagation zone; (c) the fatigue crack propagation zone; (d) the fast fracture zone

The depth of the decarburized layer was determined by the metallographic method M [17] on the transverse sections (see Table 1, sample 2) contrasted in 4% alcohol solution of nitric acid, at magnifications of 65–100 times.



a b

Fig. 3. Microstructures of non-etched microsections (see Table 1, sample 1)

For a spring with a wire diameter of more than 8 mm, made of rolled products, according to the standards [15], the one-side depth of the decarburized layer cannot exceed 2% of the allowable depth of the decarburization in total.

Microstructural study of the spring after operation, having a structure of troostite of tempering, found no traces of decarburization, even at the recommended allowable magnification of 500 times (Fig. 4).

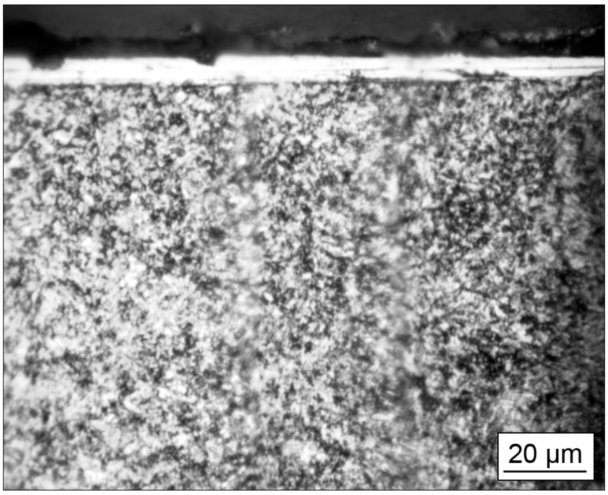


Fig. 4. Microstructure of the spring of the Ford Fiesta car after heat treatment and application of a protective surface coating (after operation)

The standard recommends for steels with a structure in which it is difficult to detect the decarburized layer, to carry out additional heat treatment – normalizing or annealing in conditions that exclude decarburization or carburization. In order to clarify the structural features of decarburization, sample 3 (Table 1) was annealed, and its microstructure was examined after etching. No traces of decarburization were detected. Therefore, the quality of the spring on the decarburization meets the requirements of the standard.

Springs according to DSTU GOST 13766:2008 [18] are strengthened by heat treatment (hardening at 870°C with cooling in oil and tempering at 470°C) with subsequent shot peening. After such treatment, their hardness should be 47.5–53.5 HRC with a deviation of ± 4 units. Then the springs are loaded at least 3 times to the touch of the adjacent coils or to the certain height. Permissible deviation of the stiffness from nominal is ± 3%. Springs with a wire diameter of more than 8 mm are coiled in a heated state. The average hardness of the investigated spring, measured by the Vickers method [19], was 580 HV, which completely meets the requirements for the manufacture of springs according to [18]. The ultimate tensile strength of steel, calculated from the value of hardness according to [20], is: $R_{\mathrm{m}} = 3.2 \cdot \mathrm{HV} = 1856$ MPa.

The chemical composition of the steel of the rear suspension spring of the Ford Fiesta car was determined by X-ray fluorescence spectral analysis using an ElvaX device [21]. The results are presented in Table 2.

Table 2

Chemical composition of the steel of the rear suspension spring of the Ford Fiesta car

Atomic number	Element	Intensity	Element concentration, %
26	Fe	1668603	97.5076 ± 0.0312
14	Si	8404	1.1603 ± 0.0225
25	Mn	9421	0.6967 ± 0.0321
24	Cr	14028	0.6495 ± 0.0303
15	P	3715	0.0222 ± 0.0168
13	Al	301	0.0972 ± 0.0398
28	Ni	100	0.0143 ± 0.0213
16	S	737	0.0127 ± 0.0045

Since the device does not determine the content of light elements (up to atomic number Z = 11), the carbon content was determined metallographically by the structure in the annealed (equilibrium) state (Fig. 5). An approximate estimate of the carbon content in the spring steel was performed according to the standard DSTU 7175:2010 [22]. By comparing the equilibrium microstructure of the spring (Fig. 5) with scales of the standard, it is established that the microstructure corresponds to grades 3 – 4 on the scale 7. This indicates the content of pearlite in the structure of steel 70–80%, and ferrite – 30–20%. Thus, the approximate carbon content in the steel is 0.56 to 0.64%.

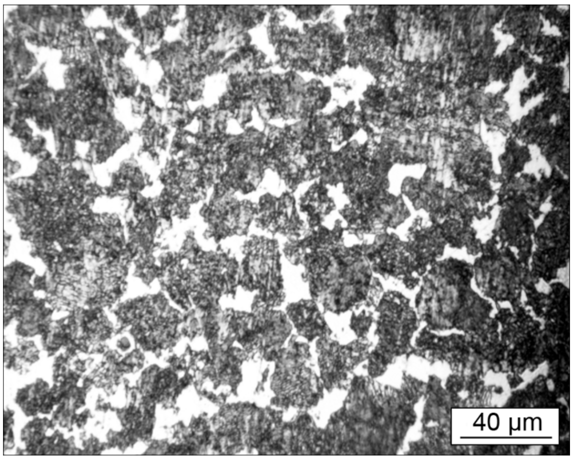


Fig. 5. Microstructure of the spring steel after annealing

The refinement of the carbon content in the steel structure was performed using a software product for image processing analysis ImageJ [23]. The images obtained by optical microscopy were processed to accurately determine the area of the dark component of the structure – pearlite. The determined amount of pearlite was 82%, which corresponds to the carbon content in the steel of 0.63%. In this way, the approximate chemical composition of the spring steel has been established (Table 3).

The Ford company uses suspension springs made of the 54SiCr6 spring steel (DIN EN 10089:2003 [24]) by H&R company [25] in Ford Fiesta cars. The closest domestic analog of this steel is spring steel of the 60C2A grade in accordance with DSTU 8429:2015 [15]. The chemical composition and mechanical properties of these steels in comparison with the steel of the investigated spring are presented in Tables 3 and 4, respectively.

Chromium in these steels increases the strength limit, hardness, hardenability, wear resistance, and corrosion resistance. Silicon, which is used to deoxidize steels, has a similar but weaker effect on these mechanical properties [26]. Decarburization, which can be caused by silicon, is prevented by reducing its content in steel to 1.2% and adding chromium.

Table 3

Comparison of the chemical composition of the steel of the investigated spring and its analogs used for manufacturing springs [15, 24]

Steel grade	Standard	Chemical composition, %					
		C	Si	Mn	Cr	P	S
Sample 1	-	0.63	1.16	0.69	0.65	0.022	0.013
54SiCr6	DIN EN 10089-2003	0.51 – 0.59	1.2 – 1.6	0.5 – 0.8	0.5 – 0.8	0.025	0.025
60C2A	DSTU 8429:2015	0.58 – 0.63	1.6 – 2	0.6 – 0.9	0.3	0.025	0.025

To protect the springs from premature failure under the influence of the atmospheric environment, they are covered with a special protective coating. The protective layer must be dense, non-porous, and must not impair the mechanical properties of the springs. Metal electrolytic coatings (chromium, nickel, cadmium, zinc, etc.) and chemical ones (oxidation, phosphating) are the most common types of coatings for corrosion protection of springs.

Table 4

Mechanical properties of the steels used for manufacturing springs [15, 24]

Steel grade	R_m (MPa)	HRC
Sample 1	1856	49.2
54SiCr6	1450 - 1750	44.5-50
60C2A	1900	44.5-63

Many car spring manufacturers use zinc phosphating, which provides good adhesion to the paint layer, for corrosion protection. To protect against mechanical damage, stone and rubble impacts, a thicker layer (for example, powder epoxy coating), which absorbs the impact energy, is formed above the corrosion-resistant layer.

Microstructural studies of the spring showed that a protective coating was applied to its surface (Fig. 4). The thickness of the spring coating, which was determined by the results of three measurements, ranged from 6 to 7 µm.

The results of X-ray fluorescence spectral analysis of the exfoliated piece of coating are presented in Table 5.

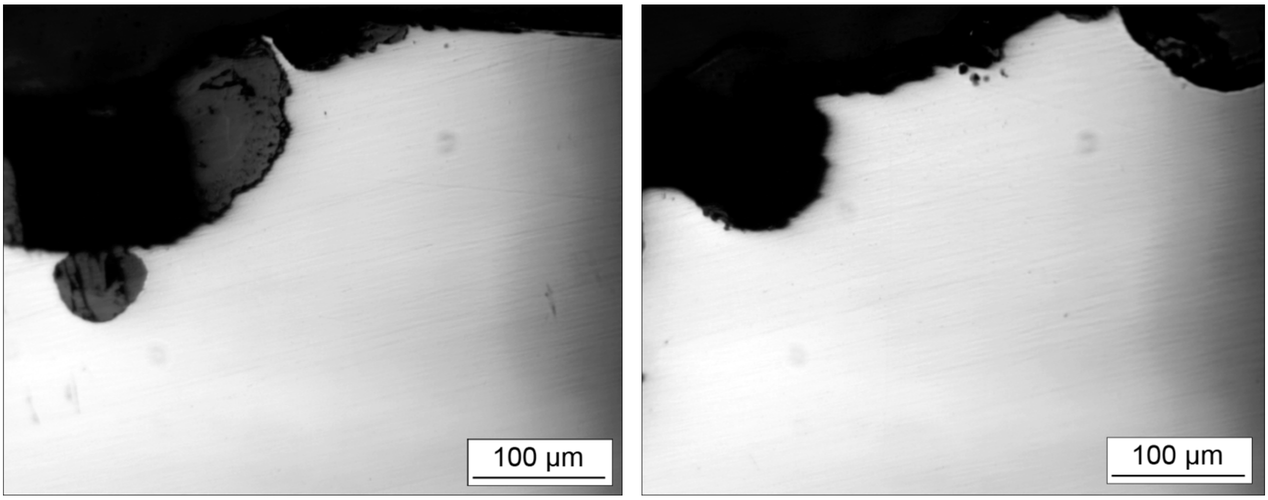
Table 5

Chemical composition of the protective coating on the investigated spring

Atomic number	Element	Intensity	Element concentration, %
56	Ba	115621	77.6630 ± 0.3820
26	Fe	1029018	10.0422 ± 0.0498
20	Ca	186826	5.8198 ± 0.0396
14	Si	37050	4.1096 ± 0.0556
13	Al	2874	1.0840 ± 0.0800
16	S	39574	0.9175 ± 0.0134
15	P	3592	0.3176 ± 0.0323
38	Sr	37947	0.0335 ± 0.0005
30	Zn	2005	0.0054 ± 0.0004
24	Cr	227	0.0036 ± 0.0069
29	Cu	655	0.0028 ± 0.0005
33	As	647	0.0010 ± 0.0003

For suspension springs produced by H&R company in Germany [25], which are made of the 54SiCr6 spring steel, protective polymer coatings are used. They are formed on the surface of a spring by vortex spraying of powdery polymer compositions. Unfortunately, according to the chemical composition determined by X-ray fluorescence analysis (Table 5), it is quite difficult to determine the composition of the powder material of the polymers that were used to form the protective coating on the investigated spring. In the Ukrainian industry, a protective coating for such springs is usually formed in several layers: a phosphatized layer, a primer layer, and two layers of varnish.

Visual assessment of the coating according to DSTU 3830-98 [27] and microstructural studies of the surface layer of the spring after operation revealed corrosion damage in places of exfoliation of the protective coating (Figs. 1 and 6). External inspection of the spring after operation showed that the coating was exfoliated on large surfaces (Fig. 1). The metallographic analysis revealed non-uniform selective corrosion, which causes exfoliation of the protective coating and spreads to the depth of the product in the form of pitting damage (Fig. 6). One of such deep pits became the initiation site of the main fatigue crack in the spring.



a b

Fig. 6. Microstructure of corrosion damage to the spring surface in places of exfoliation of the protective coating

Conclusions

The research conducted in this work was aimed at identifying the cause of the failure of the motor vehicle rear suspension spring. No technological or operational damages, such as cracks, dents, scratches, traces of the tool, were observed on the surface of the spring. The structure and mechanical properties of the spring material meet the standards. No crack initiation, caused by non-metallic inclusions, was found in the material of the fractured spring.

Instead, extensive exfoliation of the protective coating was found. Local corrosion damage in the form of deep pits, which formed in unprotected areas under the influence of operational factors, caused fatigue fracture of the middle coil of the barrel-shaped spring, which operates under conditions of more severe stress in comparison with other coils. The analysis of deformation fields performed in the work [28] confirms the fact that in progressive springs, the central coils are most deformed in contrast to linear cylindrical springs, in which the deformation of coils is the same.

Thus, the cause of the failure of the rear suspension spring of the car was the corrosion fatigue of the material due to the simultaneous action of the corrosive environment and cyclic alternate loading.

The research can be used to understand the importance of adhesive strength and wear resistance of protective coatings on the spring surface. Their local exfoliation causes subsequent corrosion damage to the spring, which stimulates its fatigue fracture.

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