INVESTIGATION OF FAILURE CAUSES OF HELICAL COMPRESSION SPRINGS

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Abstract

Compression helical springs operate frequently under varying loads and deflections. High strength steels are typically used by the manufacturers, but high UTS value should not degrade toughness and fatigue resistance, which can be achieved by control of steel composition and proper heat treatment. In this paper was investigated failure of helical compression springs used on a train coach. Analysis included assessment of mechanical properties and observation of microstructure and fracture surfaces. Provided springs were made from 51CrV4 steel from different heat numbers. Results of tensile test showed high ultimate tensile strength, well above declared material properties but lower elongation. Nominal energies of Charpy impact tests were less than 20 % of required values. Chemical composition of steel complied with specification. Fractography analysis in SEM revealed brittle fracture on the whole surface without any striations otherwise indicating fatigue failure. Observation of microstructure revealed tempered martensite in whole cross-section without distinctive segregations, but prior austenite grain size was larger than specified almost by the factor of two. It was concluded that cause of failure was synergic effect of larger grain size, quenched microstructure and high UTS resulting in low fracture toughness and resistance to impact loadings.

Keywords: Spring steel, fracture, mechanical testing, microstructure, fracture toughness

1. INTRODUCTION

Helical compression springs or coil springs are one of the primary elastic members of the vehicles suspension systems and serves as connection between the wheels and the rest of a body. Their primary function is to absorb energy and dampen the shocks received by the wheel. This absorption and following release of energy comes through elastic deformation and returning to initial length when unloaded. These dynamic operating conditions mean that helical springs are prone to failures, very often by fatigue mechanism but another failure mode is also possible if the working conditions or material properties of spring are not acceptable. Raw materials defect, surface imperfections, improper heat treatment, corrosion and decarburization are generally recognized causes of fatigue failure of suspension spring. Roughness of the material surface and presence of inclusions also acts as a stress raiser in the springs [1,2].

Trends in the vehicles industry aim for continuous weight reduction as well as improvement of coil performance. This means that springs are nowadays subjected to larger stress compared to previous generations, placing higher demands on material properties and manufacturing quality. Spring manufacturers uses several types of steel, but high strength steel are regularly used, in the range strength from 1200 to 1800 MPa. High quality springs require also fine-grained microstructure with low inclusions content [3]. But final properties depend also on hot forming processes and final heat treatment. Overall, the use of spring steels with good hardenability to provide required mechanical properties, high ductility and toughness is recommended [4].

Efforts to develop high strength spring steels have introduced processes to improve properties not only by optimum chemical composition and heat treatment, but through micro-alloying, shot-peening or grain-refinement. Lowering austenitizing temperature increases tensile strength of martensitic steels and addition of Nb and V has been found beneficial due to precipitation of finely-dispersed carbonitrides [4]

One of the commonly used is hypo-eutectoid steel 51CrV4, which is usually heat treated in furnace to the temperature 30 to 50 °C above A_{c3} for the homogenization of austenite and subsequently quenched and tempered. The tempering diagram gives information about the mechanical properties as a function of the tempering temperatures. Minimal impact toughness measured on Charpy-V specimens must be given in case of spring steel, preferably also with the values of fracture toughness. [5]

In this paper were investigated causes of failure of helical compression springs used on bogie subsystem of train coach, which have failed in service. The bogie/truck subsystem design of locomotives ensures the load distribution and ride comfort. The bogie is consisted of primary and secondary suspensions. The primary suspension connects wheel set to the bogie frame and its main function is to isolate the body from track irregularities, to give the passengers an acceptably comfortable ride and to maintain vehicle track loads within acceptable limits. The secondary suspension function is to connect the bogie frame to the body and provide the required stiffness and freedom of movement in all coordinates. [6] Springs were made from heat treated 51CrV4 steel. No further information about specific operating conditions or events preceding the fracture occurrence was given.

2. EXPERIMENTAL PROCEDURE

2.1. Visual observation

Two helical springs were provided for investigation, designated by their respective numbers - 1286 and 1490. Springs type were of open and ground type, which means the ends were grounded flat and last half-coil is inactive. Fracture surface was located on the first active coil in case of No. 1490 spring, while the rest of No. 1290 was sawed off - **Figure 1** and no information of fracture position in respect to spring was given. Polymer-based black coating which protects surface from corrosion was severely worn. Fracture surfaces were not protected from the environment, therefore were covered by uniform layer of rust. Surfaces were cleansed by Nital etchant for further inspection. Appearance of the fracture surface area pointed out area of origin which was later observed by scanning electron microscope - **Figure 2**. Edge of the fracture surface extended at angle 45° towards the spring axis, which is typical for torsional failure under cyclic torsion [1,2]. An artefact of bend edge is visible on spring No. 1286 but located aside from the area of possible crack origin and was not taken into consideration of fracture causes.

Figure 1 Fractured helical springs. (a) No. 1490 and (b) No. 1286

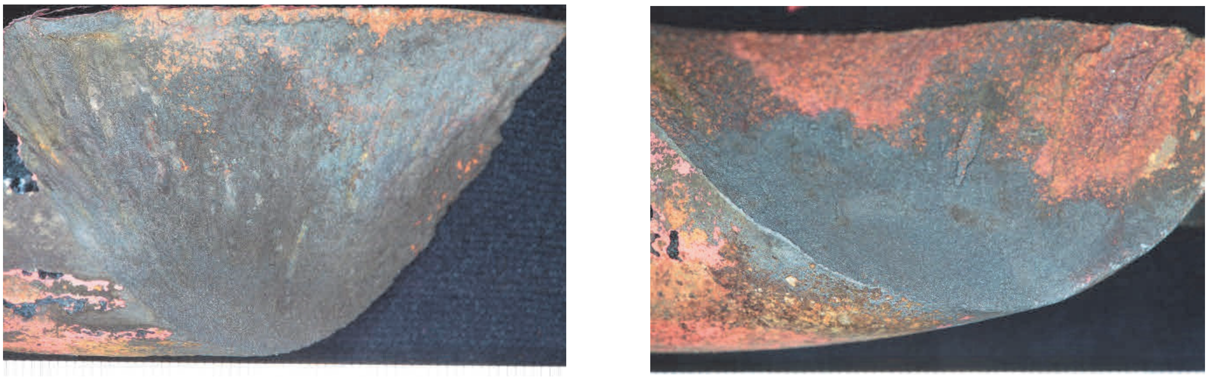

Figure 2 Close-up of the cleansed fracture surfaces (a) No. 1490 and (b) No. 1286

2.2. Microstructure observation

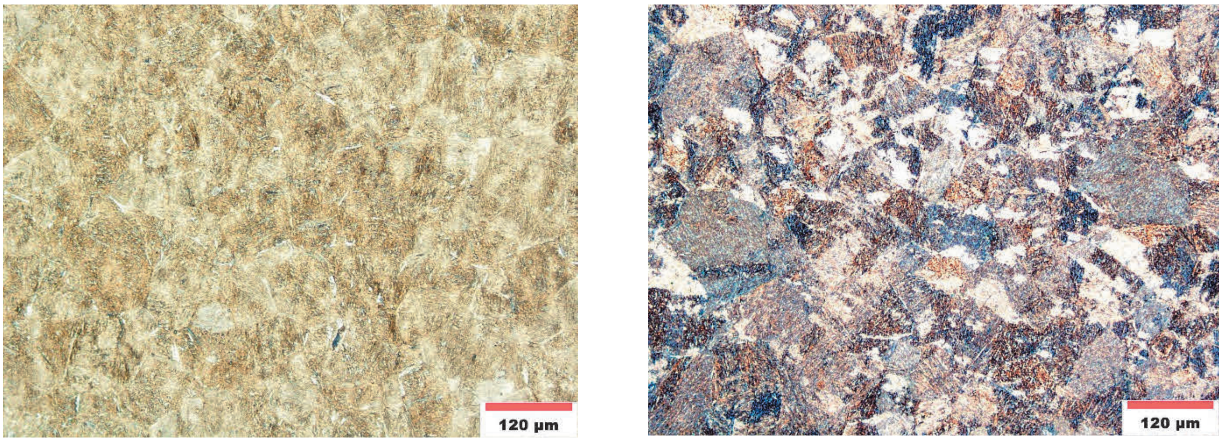

Figure 3 Microstructure of spring No. 1286 after etching in (a) Nital 4 % and (b) Villela

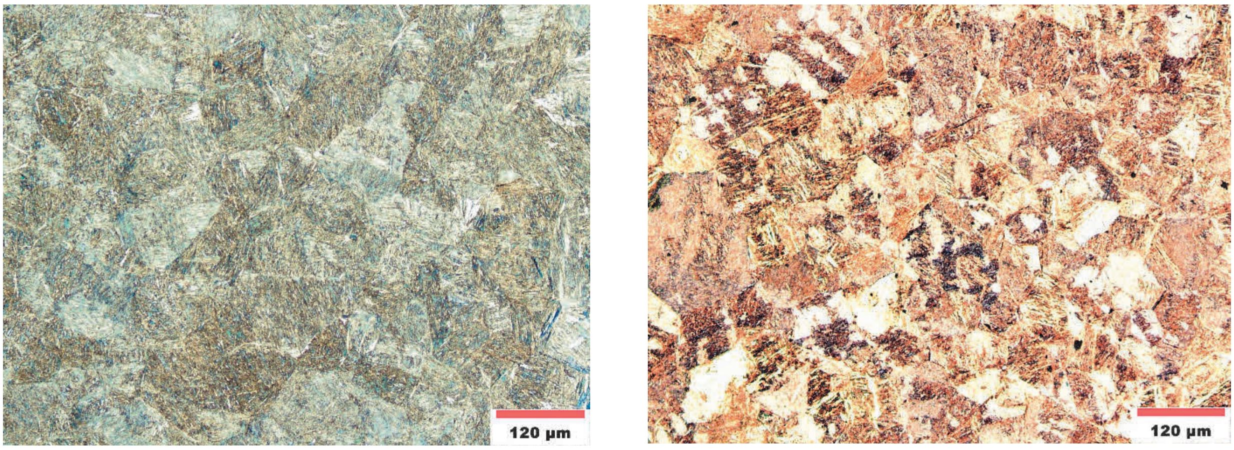

Figure 4 Microstructure of spring No. 1490 after etching in (a) Nital 4% and (b) Villela

Standard metallography specimens were prepared from the area close to fracture surface. Prevailing oxide type inclusions were observed in polished condition but not evaluated according to standard. Nital 4 % etchant was used to reveal microstructure which consisted of tempered martensite in the whole cross-section with minor decarburization on the surface. Depth of decarburization was later estimated by hardness testing. Furthermore, specimens were etched in Villella's reagent to evaluate primary austenitic grain size. Lineal intercept procedure was used to determine the grain size number G which were found to be G = 4 for both specimens. Grain size was consistent within whole diameter of the springs. This grain size was found to be inadequate as the grain size of manufactured springs must be at least G = 8. Observed microstructures of springs are shown on **Figure 3** and **Figure 4** in etched conditions.

2.3. Mechanical testing and chemical analysis

Two specimens for tensile test and three for Charpy impact test were prepared from each spring to test mechanical properties by respective standards. Obtained results are presented in the **Tables 1** and **2**. Values of yield strength and ultimate tensile strength were found to be higher than specified by the manufacturer, in average by 30 MPa for YS but considerably higher in case of UTS - average of 1742 MPa vs. specified 1500 MPa for spring No. 1286 and 1725 MPa vs. 1563 MPa for spring No. 1490. On the other hand, elongation A_5 should reach values up to 9.4% and 10.5 % respectively but was found to be lower.

Table 1 Results of the tensile testing

Specimen	E	YS	UTS	F_m	L_0	d_0	S_0	L_u	A_5	Z
	GPa	MPa	MPa	kN	mm	mm	mm^2	mm	%	%
1286/1	209	1599	1754	87,94	40	7.99	50.14	42.5	6.6	23
1286/2	211	1535	1749	87,69	40	7.97	49.89	42.43	6.7	24
1490/1	206	1537	1725	85,85	40	7.96	49.76	4.75	6.3	24
1490/2	213	1526	1726	85,69	40	7.95	49.64	42.24	6	23

Table 2 Results of the Charpy impact test

Specimen no.	Impact energy [J]		Notch toughness KCU5 [J / cm^2]	
1286-1	2.46	2.27	4.91	4.55
1286-2	2.22		4.44	
1286-3	2.14		4.29	
1490-1	1.61	1.81	3.21	3.62
1490-2	1.68		3.37	
1490-3	2.14		4.29	

Results of Charpy impact tests conducted on KU5 specimens pointed out very low impact energy and overall notch toughness, on average 4.55 J / cm^2 for spring No. 1286 and 3.62 J / cm^2 for No. 1490. Material certificate specifies values of notch toughness to be higher than 50 J / cm^2.

Hardness HRC was measured across the diameter from the surface to the centre with average hardness 45 HRC for spring No. 1286 and 47 HRC for No.1490. Hardness declared by the manufacturer is within the range from 426 to 527 HBW, therefore hardness values were adequate. Decarburization of the surface was tested by HV 0.1 hardness testing according to standard to the depth of 1730 μm with the row of 12 indentations. Depth of decarburization as the depth, where the hardness reached that of the core was found to be around 400 μm.

Chemical composition of spring materials was determined by glow discharge spectrometer. Results are presented in **Table 3**. Composition was found to be in accordance with the provided standard of the manufacturer for 51CrV4 steel grade.

Table 3 Chemical composition of spring materials 51CrV4 (wt. %)

Specimen	C	Mn	Si	P	S	Cu	Ni	Cr	Mo	V	Al-c	H (ppm)
1286	0.541	1.06	0.33	0.009	0.0118	0.020	0.031	1.183	0.008	0.170	<0.002	1.1
1490	0.534	1.05	0.33	0.009	0.0116	0.020	0.024	1.180	0.006	0.161	<0.002	1.6

2.4. Fractography analysis

Fracture surfaces and the areas of probable fracture initiation based on the macro observation were studied in SEM. In addition, fracture surfaces of Charpy impact test specimens were also observed. Specific defect acting as a notch or stress raiser and precise origin of fracture was not observed on the surface of the springs, but such identification was found to be difficult due to state of the surface with multiple pits of uniform corrosion. Fracture surfaces of both springs consisted of brittle intergranular fracture. **Figure 5** shows edge of the fracture in the possible initiation area of the No. 1286 spring, where pitted surface with remnants of rust are visible in backscattered electrons. **Figure 6** shows higher detail of the fracture surface of specimen from impact test with distinctly visible grains which proves low energy fracture and low toughness of the springs.

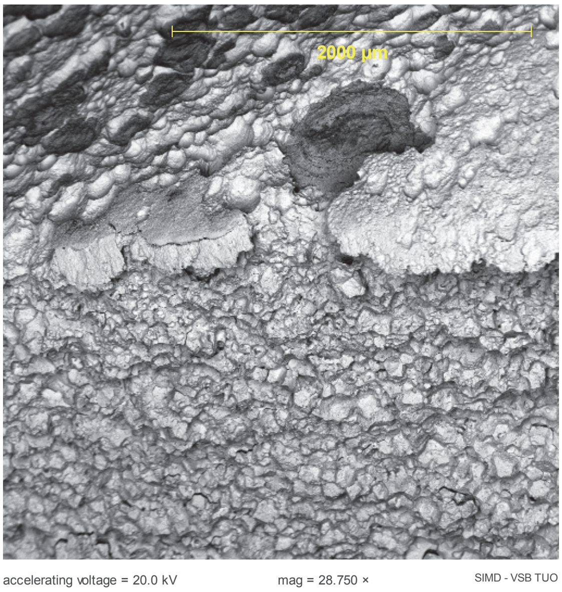

Figure 5 Edge of the fracture - spring No. 1286

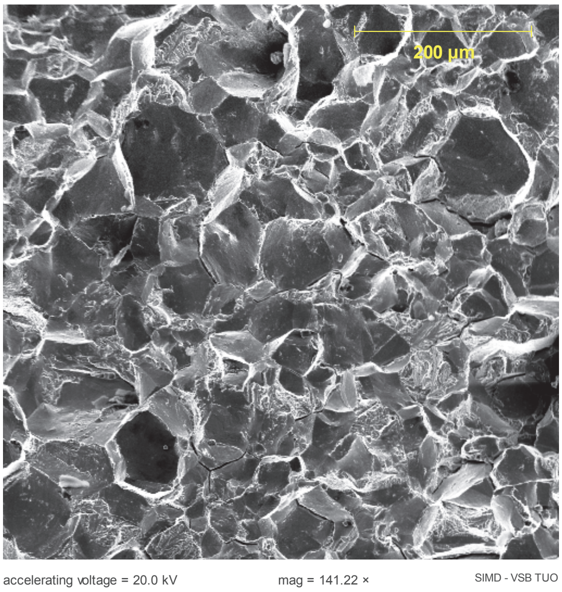

Figure 6 Fracture surface of impact specimen

3. CONCLUSION

Thorough failure analysis of failed helical compression springs was conducted. This included visual observation of fracture surfaces, determination of mechanical properties, microstructure observation and fractography in SEM. Tensile properties, hardness and chemical composition of the material met specifications. Results of impact test showed very low notch toughness, well below specified values. Further finding from the observation of microstructure was that austenitic grain size G was measured to be G = 4 instead of specified G = 8. It must be pointed out that this condition did not influence results of tensile tests significantly, on the contrary UTS of the material was higher than required, although with lower elongation A_5. Influence of the surface corrosion would require further analysis, but it must be pointed out that protective paint layer should not be severely worn as it was observed. It was concluded that springs failed due to sudden brittle fracture, most likely caused by sudden impact loading. Primary cause of failure was attributed to the fault in the process of heat treatment resulting in austenitic grain growth, lower cohesive strength of grain boundaries and overall low toughness of the springs.

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REFERENCES

[1] VUKELIC, G., BRCIC, M. Failure analysis of a motor vehicle coil spring. *Procedia Structural Integrity*, 2016, vol. 2, pp 2944-2950.

[2] ZHU, Y., WANG, Y., HUANG, Y. Failure analysis of a helical compression spring for a heavy vehicle's suspension systé. *Case Studies in Engineering Failure Analysis*, 2014, vol. 2, no. 2, pp 169-173.

[3] ŠUSTARŠIC, B., BORKOVIČ, P., ECHLSEDER, W., GESTMAYR, G., JAVIDI, A., SENČIČ, B. Fatigue strength and microstructural features of spring steel. *Structural Integrity and Life*, 2011, vol. 11, pp 27-34.

[4] ŽUŽEK, B., SEDLAČEK, M., PODGORNIK, B. Effect of segregations on mechanical properties and crack propagation in spring steel. *Frattura ed Integrità Strutturale*, 2015, vol. 34, pp 160-168.

[5] SENČIČ, B., LESKOVŠEK, V. Fracture toughness of the vacuum-heat-treated spring steel 51CrV4. *Materials and technology*, 2011, vol. 45, pp 67-73.

[6] GHATE, P., SHANKAPAL S. R., GOWDA, M. H. Failure Investigation of a Freight Locomotive

Suspension Spring and Redesign of the spring for Durability and ride index. *SASTECH Journal*, 2012, vol 11, no. 2, pp 23-29.