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# Failure analysis of a helical compression spring for a heavy vehicle's suspension system

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ABSTRACT

This paper analyzed why a compression coil spring fractured at the transition position from the bearing coil to the first active coil in service, while the nominal stress here should always be much less than that at the inside coil position of a fully active coil. Visual observations indicated that a wear scar was formed on the first active coil and the fracture surface showed radiating ridges emanating from the wear scar. Scanning electron microscopy examination showed crescent shaped region and beach marks, typical of fatigue failure. ZnCaph phosphate layer and painting around the contact zone were worn out due to contact and friction and resulted in corrosion and corrosion pits induced local stress concentration. Stress analysis indicated severe stress singularities at the edges of the contact zone, which facilitated cycle slip and fatigue crack nucleation. Recommendations were also made for improving the fatigue performance of the suspension springs.



## 1. Background

Helical compression springs, as one of the primary elastic members of the suspension system of vehicles, are widely used in auto industry. They connect the wheel to the body elastically and store the energy to absorb and smooth out shocks that are received by the wheel from road irregularities and transmitted to the body. This dynamic service loading condition often results in fatigue failure of the suspension spring in a variety of ways. Raw materials defect, surface imperfections, improper heat treatment, corrosion and decarburization are generally recognized causes of fatigue failure of suspension spring [1]. In service, the stress on the inner surface of an active coil of the helical spring is the position of maximum stress and the coil surface itself is vulnerable to imperfections in materials and surface integrity that serve as stress concentration points bringing about fatigue crack initiation [2]. Additionally, it is recognized that compression springs often fractured at the transition position from the bearing coil to the first active coil [3]. The following aspects such as poor shot peening because of no gap or small gap between the bearing coil and the first active coil [4], bending stress due to pivoting of the first active coil about the end tip [4], larger eccentricity of the loading force induced larger maximum net-tensile stress [5], and corrosion due to collection of corrosive fluid in the smaller gap between the bearing coil and the first active coil. The above summary shows that a variety of factors may cause fatigue failure of helical compression springs in engineering applications. In fact, it is often the concurrent acts of several of the above causes that results in spring fatigue. Our recent works about failure

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analysis of a helical compression springs of a heavy vehicle revealed that stress singularity due to non-Hertzian contact between the bearing coil and the first active coil played critical role in the fatigue crack initiation. This paper emphasized contact stress analysis in addition to fractographic analysis of the fracture surface, microstructure and chemical analysis of the spring material.

A heavy vehicle's suspension helical compression spring fractured in service just at the transition position from the bearing coil to the first active coil. The spring, having closed ends design, with total length of 532 mm, coil radius of 82.5 mm, seven active coils and two bearing coils, was cold-coiled from a wire of36 mm in diameter. The spring was made of 60Si2CrVA [6], a high strength spring steel with ultimate tensile strength of 1860 MPa and yielding stress of 1665 MPa. The spring was quenched and tempered with typical microstructure of tempered troostite. Before painting, the spring was grit blasted and phosphated.

## 2. Experimental procedures

### 2.1. Visual observations

As Fig. 1 suggests, the edge of the fracture surface extended at an angle of 45° with respect to the wire's axis, e.g., cracks grew as a spiral around the surface of the axis, typical of torsional fatigue of a round axle under cyclic torsion. Wear scar could be seen clearly on the upper surface of the first active coil due to contact and friction with the bearing coil and the wear scar, as indicated by the arrow in Fig. 1, was flat and smooth. Painting close to the wear scar was disbonded, resulted in direct exposure of metal to environment. In Fig. 1(b), radiating ridges radiating from the wear scar could be caught easily on the fracture surface, suggesting metal fatigue, and the focus of the radiating ridges was supposed to be the site of fatigue origin. A plastic extrusion as a result of contact and impact, near the fatigue origin, was also visible, referring to the arrow in Fig. 1(b). In addition, contamination and corrosion product due to exposure to the environment after the fracture could also be observed on the fracture surface.

### 2.2. Scanning electron microscopy

A fracture surface specimen was cut near the wear scar of the failed spring and was cleaned ultrasonically in acetone to remove the contamination and corrosion, whereafter, a QUANT-200 scanning electron microscope (SEM) was used to examine the detailed features of the fracture surface. Refer to Fig. 2, a crescent shaped region and beach marks were visible, which are typical fatigue features. Corrosion pits can be observed on the surface of the spring, especially, a corrosion pit was formed at the center of the fatigue origin. Fig. 3(a) is a close view of the fatigue origin indicated by the arrow in Fig. 2. Fig. 3(b)

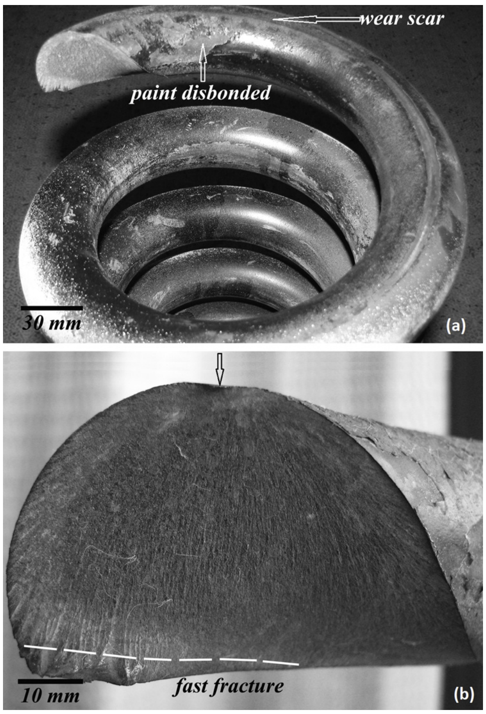


**Fig. 1.** Fracture photographs of the failed spring. (a) Fractured spring and (b) close-up of the fracture surface.

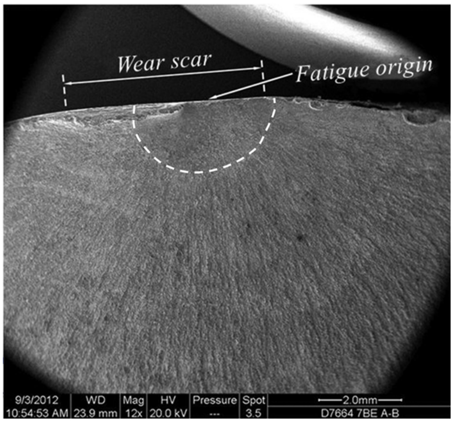


**Fig. 2.** SEM photograph of the fracture surface after ultrasonic cleaning.

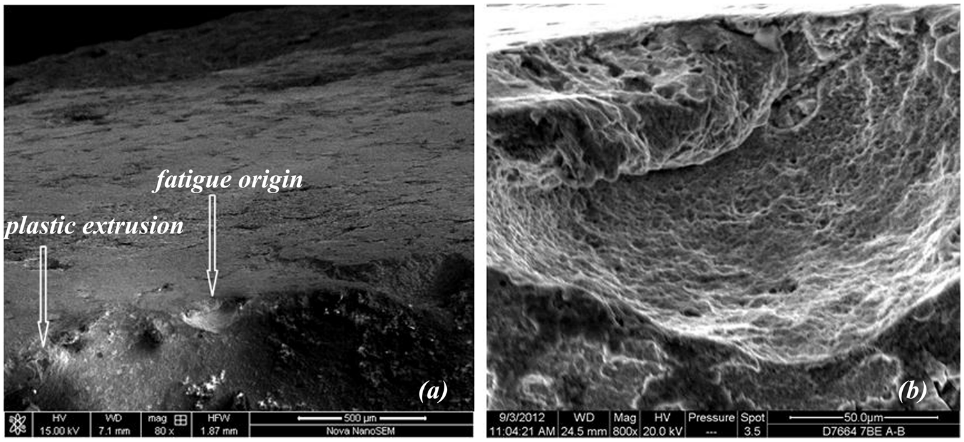


**Fig. 3.** SEM photographs of the fatigue origin after ultrasonic cleaning. (a) Close view of the fatigue origin and (b) magnified view of the corrosion pit, see the right arrow in (a).

is a SEM image showing a magnified view of the corrosion pit with depth of about 100 $\mu$m. It is believed that it was the corrosion pit which induced stress concentration and contributed to fatigue nucleation. Corrosion was formed as a result of disbonding of the protecting paint and rupture of the ZnCaph phosphate layer due to impact and wear of the closed end. Noteworthy is that the fatigue origin (focus of the radiating ridges or center of the crescent), as indicated by the white arrow, was located at the right hand side of the wear scar. The reason for this phenomenon will be discussed latter in Section 3.

## 3. Stress analysis

As previously indicated that the fatigue origin was located at the right hand side of the wear scar, this was supposed to be correlated to the contact and friction behavior of the closed ends. In fact, during service the dynamic load and shocks received by the wheels from road irregularities resulted in contact and impact between the bearing coil and the first active coil due to the closed ends design. As a result of repeated contact and impact, the contact surfaces were gradually worn out and non-Hertzian contact took place accordingly. In what followed, a finite element model was built to simulate the contact behavior of the closed ends so as to understand what roles the contact stress has played in the fatigue failure.

In consideration of the fact that the length of the wire in the circumferential direction of the spring coil is much larger than the diameter of the wire, a plane strain model representing the contact between the bearing coil and the first active coil was built, where the width of the contact zone (5.5 mm) was evaluated according to the SEM photograph of the fracture surface, referring to Fig. 2. A pressure load of 200 MPa was applied on top of the bearing coil and nodes on bottom of the working coil were restrained from motion. Fig. 4(a) and (b) showed the contact pressure and the shear stress profiles, respectively. It was obvious that both the contact pressure and the shear stress exhibited severe singularities at the edges of the contact zone. While the higher contact pressure implied severer wear, it was the singularities in shear stress that facilitated cycle slip and contributed to crack nucleation. As a consequence, fatigue origin was not initiated at the middle of the contact zone. Taking into consideration that wear was a gradual process in service, so that the width of the contact zone increased with

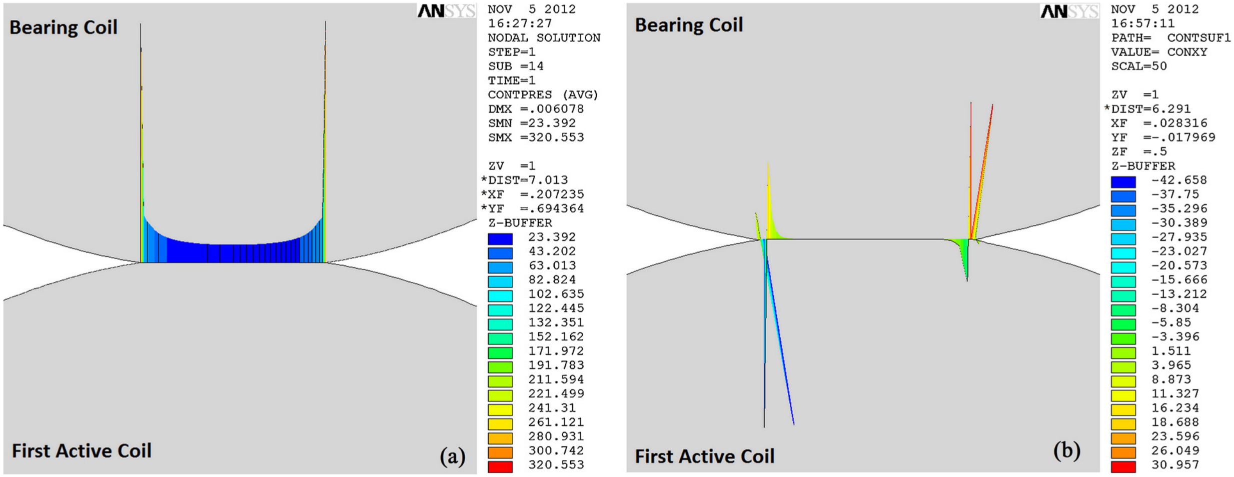


**Fig. 4.** FEM results of stress distributions in the contact zone. (a) Contact pressure and (b) shear stress.

time. At earlier stage of the contact, stress singularity at the edge of the contact caused fatigue crack initiation, whereafter, the fatigue crack developed continuously while the contact zone increased gradually. As a result, the fatigue origin was not precisely at the edge of the final contact zone.

## 4. Chemical analysis and microstructure observation

### *4.1. Chemical analysis*

An examination of material composition was analyzed by Direct Reading Spectrometer, and showed that the compositions of failed spring were within the specification limits of 60Si2CrVA spring steel grade [6] (refer to Table 1).

### *4.2. Microstructure observation*

A specimen was cut from the failed spring (near the fracture surface), polished and etched using 4% nital as standard metallography techniques to reveal microstructures. Optical microscopy of the spring sample showed a fine tempered troostite microstructure [6].

### *4.3. Hardness measurement*

A hardness survey was made across the cross section of the metallographically prepared sample of the failed spring. The sample showed hardness value of 52.3HRC, met the criterion of the spring steel [6].

## 5. Results and discussion

Microstructure and hardness met specifications, and the chemical composition of spring steel conformed to the spring manufacture's specification.

Crescent shaped region, beach marks and radiating ridges on the fracture surface ascertained that the fracture of the spring was caused by metal fatigue and the crack origin was located at the right hand side of the wear scar between the bearing coil and the first active coil.

Visual and SEM analyses revealed that dynamic service loading resulted in disbond of surface painting and worn out of the phosphate layer due to the closed ends design.

**Table 1**
Chemical composition of 60Si2CrVA/wt%.

| | Composition | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | C | Si | Mn | Cr | V | Ni | P | S | Cu |
| GB/T1222-1984 | 0.56–0.64 | 1.40–1.80 | 0.40–0.70 | 0.90–1.20 | 0.10–0.20 | ≤0.35 | ≤0.030 | ≤0.030 | ≤0.25 |
| Failed spring | 0.56 | 1.57 | 0.54 | 0.95 | 0.16 | 0.12 | 0.008 | 0.005 | 0.07 |

Corrosion pits were formed as a result of metal exposure to the environment atmosphere and collection of fluid at the small gap between bearing coil and the first active coil. Corrosion pits acted as local stress raiser that accelerated fatigue crack initiation and propagation.

Contact stress analysis showed that stress singularities presented at the edges of the contact zone, and it was the severer shear stress at these locations that facilitated cycle slip and resulted in crack nucleation. This result interpreted the observation that fatigue initiated at the right hand side of the wear scar.

In view of the above analyses, it can be concluded that it was the closed ends design that resulted in worn of the coil surface and corrosion due to collection of fluid at the contact region. The corrosion pits, in turn, acted as local stress raiser that promoted fatigue initiation and the stress singularities exhibited at the edges of the non-Hertzian contact facilitated cycle slip and determined crack initiation site. Once the initial crack was formed, it propagated by the act of the maximum principal tensile stress, whose direction subtended an angle of approximately 45° with the spring wire axis [5]. At last, the suspension spring failed due to over loading of the remained section of the wire.

## 6. Conclusions and recommendations

(1) It was the concurrent acts of the wear, corrosion together with stress singularities at the contact zone of the closed ends that resulted in fatigue crack initiation of the suspension spring.
(2) Once the initial crack was formed, it was the maximum principal tensile stress that forced the crack to propagate along the direction of 45° with the spring wire axis.
(3) It is strongly recommended to adopt a non-closed ends design in order to avoid wear and corrosion of the suspension spring.
(4) Solid lubrication film, if possible, can be used in the closed ends to greatly reduce the fretting and corrosion.
(5) Local hard facing to enhance the wear resistance of the end coils can be done if necessary.

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