Analysis of surface failure of coil spring in passenger vehicle suspension system

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Abstract. This study aims to investigate the failure of a coil spring. The examination of the chemical composition, hardness testing and observation of the fracture surface were performed, and the shear stress occurring on the coil spring was calculated. The results indicated that the inner side of the coil spring was harder than the outer side. Furthermore, the failure was fatigue failure; as shown by the presence of the crack initiation and the benchmarks. The crack initiation occurred because of the stress concentration at one point due to fretting.

1. Introduction
A coil spring is one of the main elastic components in the suspension system of a vehicle. It is expected to not only be able to withstand vibrations but to also withstand a load due to several vehicle maneuvers such as acceleration, braking or turning while on the road. This means that a coil spring must be able to withstand, reduce and absorb the impact from loads, twisting loads and cyclic loads [1-5]. Failures of the coil spring are often due to several factors, namely defects in the raw materials, surface imperfections, improper heat treatment processes and corrosion [1,6-7]. The load acting on the spring can take the form of a tensile force, compressive force or torque (twist force). The springs generally operate with 'high working stresses' and the load varies continuously.

Coil springs often experience fatigue failure in application due to their inability to withstand dynamic loads. Fatigue is a form of failure that occurs in structures undergoing dynamic and fluctuating stresses (for example, bridges, aircraft components, and engines). In this state, failure occurs at a stress level that is lower than the tensile strength or yield at the static load. The term "fatigue" is used because this type of failure usually occurs after repeated stress or strain cycles over a long period of time [8].

Fatigue failure is a brittle fracture mechanism that consists of three stages, namely the initial crack, the crack propagation and the final fracture [9]. According to research conducted by Zhu et. al. [10] with regard to fatigue failure in coil spring, defects due to physical contact and friction caused the coil spring to break. Then, a research conducted by Kosec et. al. [11] found that fatigue failure on a coil spring occurred due to corrosion found in the fault position. Based on the studies mentioned above, it was deduced that several factors could cause failure in the coil spring. Therefore, this study was aimed at examining the cause of failure in a coil spring through an analysis of the broken surface of the coil.

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spring. It was expected that the results of the analysis would later explain the cause of the fatigue failure in the spring and recommendations could then be made to those who require them.

2. Materials and methods
In this study, some laboratory tests were conducted. The specimens for the tests are shown in Figure 1. Test on the chemical composition was carried out using a scanning electron microscope and energy dispersion X-ray spectroscopy (SEM, EDS). Furthermore, a hardness test, using the Vickers hardness testing method, was carried out to determine the hardness value of the coil spring. The principle for the testing was based on tracking or indenting the sample with a pyramid-shaped diamond indenter with a slope of about 136°. In this test, the specimen was pressed for 15 seconds with a force of 10 kg, as set on the Vickers test instrument. The test points for the surface toughness of the coil spring can be seen in Figure 2. The specimen consisted of several sides, where T was the top, I was the inner side, B was the lower side and O was the outside [7]. SEM images of the specimen were taken of the spring surface that had experienced failure. The analysis of the broken surface was carried out by means of two methods of observation. The first observation was by visual analysis and the second observation was with the aid of the SEM images. Before the testing, the specimen was designed with such a shape as to make it easier for testing.

![Figure 1. Specimens: (a) chemical composition test, (b) hardness test, (c) SEM test.](image1)

![Figure 2. Test points for surface hardness.](image2)
The torsion load that occurred in the coil spring was calculated to find the minimum and maximum torsional loads. The maximum twisting load was adjusted to the allowed twisting load of the ASTM A227 in order to ensure that the torsional load acting on the coil spring component was still in a safe condition to prevent fatigue. A Goodman diagram, based on the following equations, was used:

\[
\tau_{\text{min}} = \frac{8F_{\text{w}}PD}{\pi d^2}
\]

(1)

\[
\tau_{\text{max}} = \frac{8F_{\text{w}}PD}{\pi d^2}
\]

(2)

3. Results and discussion

From the SEM / EDS results, the chemical composition was close to the ASTM A227 standard for the material, as shown in Table 1, especially for elements C, P, S and Mn. The elements Si and Cr did not meet the ASTM A227 standard because the coil springs actually did not have a high hardness as their main characteristic. The main characteristic of the coil springs was their elasticity. The mechanical properties of the ASTM A227 material are shown in Table 2.

Table 1. Comparison of the composition of spring steel specimen with that of ASTM A227

| Material       | C   | Mn  | P   | S   | Si  | Cr  |
|----------------|-----|-----|-----|-----|-----|-----|
| Spring steel   | 0.36| 0.6 | 0   | 0.02| 0.06| 0.09|
| ASTM A227      | 0.45-0.85| 0.30-1.30| 0.04| 0.05| 0.15-0.35| 0.03|

Table 2. The mechanical properties of ASTM A227

| Shear modulus (GPa) | Tensile modulus (GPa) | Density g/cm³ | Shear stress (MPa) |
|---------------------|-----------------------|--------------|-------------------|
| 11.5x10³            | 28.6x10³              | 7700         | 700               |

The ASTM A227 standard has a carbon, C, 45%-0.85%, while the test result revealed a carbon content of 0.36%, which was within the standard and could be classified as medium carbon steel. The sulfur element, S, in a coil spring functions to form inclusions, and high levels of this element can reduce the ductility of the steel and increase the likelihood of cracking. The composition was equal to the ASTM A227 standard, which was 0.02%. The ASTM A227 standard has phosphorus, P, content of 0.04%, while the test results revealed a phosphorous content of 0%, which was in accordance with the standard. The function of silicon, Si, is to improve hardness. Unsuitable silicon content can cause the coil spring to crack easily. The ASTM A227 standard for silicon, Si, content is 0.15%-0.35%, while the test result revealed silicon content of 0.06%. This was very low compared to the ASTM A227 standard, meaning that there was a decrease in the hardness of the coil spring, thereby causing it to be easily deformed. Manganese, Mn, functions to increase the ductility of the coil spring. The ASTM A227 standard for the Manganese content is 0.30% -1.30%, while the test result showed a content of 0.60%.

The hardness distribution graph for the inner surface at each point is shown in Figure 3. It can be seen that the distribution tended to be uneven. Point 1 had the lowest hardness value (289 HVN), point 2 had a value of violence that was starting to increase (382 HVN), point 5 had the highest hardness value (455 HVN), and the distribution of violence at the next point tended to be evenly distributed to point 9 (434 HVN). The test results showed that the lower hardness was in the surface area and the higher hardness was further from the surface. This was not in accordance with the distribution of steel
in general. The increase in hardness was quite significant on the surface area, and the hardness was lower for areas further from the surface due to heat treatment and hardening of spring surface.

![Figure 3. Values of Vikers hardness (HVN)](image)

The testing of the hardness of a cross section of the thread of the spring specimens resulted in an average spring surface hardness value of 345 HVN in the T section, 417 HVN in the I section, 328 HVN in the B section and 429 HVN in the O section of the spring, as shown in Table 3. These results were in accordance with the hardness value of the ASTM A227 standard, namely 310-543 HVN. The excessively large hardness value caused a decrease in the elasticity of the spring, and when it reached the maximum load, the spring easily experienced cracks.

| Section | Hardness (HVN) |
|---------|----------------|
|         | Point 1 | Point 2 | Point 3 | Point 4 | Point 5 | Average |
| T       | 286     | 400     | 421     | 237     | 382     | 345     |
| I       | 400     | 446     | 409     | 400     | 432     | 417     |
| B       | 231     | 409     | 231     | 381     | 390     | 328     |
| O       | 392     | 392     | 434     | 471     | 458     | 429     |

Based on the results of the visual investigation, the coil spring had a brittle fracture failure, where a broken shape was formed at an angle of ±45°. It was stated that the fracture that occurred in the coil spring was tired. This fracture started from the surface, spread to the centre and broke as the load exceeded the loading capacity of the material. There was a very clear change in the dimensions or what is known as fretting wear, which occurred due to collisions with other coils; thereby inducing frictional and compressive forces on the coil spring surface. The beginning of the crack occurred at the wear area on the spring surface, which was the outer side of the spring axis, with the direction of the crack propagation being equal to the two surface contact stresses. The presence of wear on the coil spring resulted in crack initiation. Subsequent loading caused the beginning of cracks, which propagated to form a crack area. The crack area was marked by the presence of beach marks. Furthermore, the crack propagation stopped once the remaining spring section was unable to withstand the working load until it broke.

It can be stated that the coil spring, in this study, experienced fatigue fracture, characterized by the presence of beach marks. This fatigue occurred due to changing or repetitive loads. The final fracture
area that occurred looking wider than the spreading area or the initial crack area, showing the nominal stress that worked on the coil spring had exceeded the limit of the material. The SEM image with an optical enlargement of 30x showed that the crack propagation had spread to the entire surface, thereby forming a chevron pattern, which is a cone pattern, towards the beginning of the crack, as shown in Figure 4 (a). The SEM image with an optical magnification of 40x showed the crack initiation had formed a deep trench, as shown in Figure 4 (b). It is believed that these cracks were corrosion holes caused by stress concentration at one point and changes in the structure of the coil spring. Corrosion was formed due to damage to the protective paint and scars caused by pressure and friction. The next stage continued with the existence of beach marks, and finally, the coil spring broke. Ordinary beach marks were indicated by fine circular lines in the area between the beginning of the crack and the final fracture. Beach marks are more often said to represent the stages of crack propagation. The SEM image with an optical magnification of 500x (Figure 4 (c)) showed the crack initiation area and the characteristics of the fretting wear in the form of sharp holes in the fretting area such that there was a notch that caused the local stress concentration so that this area was very sensitive to the initial formation of cracks. The crack initiation was also accelerated by the shear stress due to the contact action between the coil spring and other specimens.

Figure 4. SEM images: (a) the propagation that formed a chevron pattern (b) fatigue fracture as evidenced by the presence of cracks and the shoreline (c) form of the initial crack of a screw spring and the formation of a notch

To determine the maximum torsional stress, the exact calculation was done as follows. With a thread diameter of 14 mm, an outer diameter of 80 mm, and a number of active coils, the minimum load received by one coil spring was 3064 N, and the maximum load was 3922.5 N. From the results, the minimum twist load received by one coil spring was 257.9 N/mm², and the maximum twist load was 329.2 N/mm². The ASTM A227 was wrapped under the hot condition so that the allowable torsional stress was 700 N/mm². The maximum torsional load was still below the allowable tension value.

The following Goodman diagram shows whether the dynamic load acting on the coil spring component was still in a safe condition against fatigue fractures (Figure 5). The points $\tau_{\text{min}}$ and $\tau_{\text{max}}$ were perpendicular to each other on the horizontal axis. A variation of 71.3 N/mm² was considered in the torsional stress, while the variation permitted according to the ASTM A227 standard was 700 N/mm². This means that the protection against fatigue was $\nu = \frac{700}{71.3} \approx 9.8$. It can be concluded that this was quite far from the fatigue value of the material, and therefore, the possibility of failure due to torsional stress was quite small. The shear stress received by the coil spring was within the allowable stress, but the spring still failed due to fatigue caused by a creeping crack. Cracking propagation occurred due to the continuous dynamic load and was accelerated by the frictional force and compressive force.
4. Conclusion
This study was aimed at investigating the failure of a coil spring. Early cracks occurred in the wear area. After the initial crack was formed, this became the maximum point of stress that forced the crack to spread. With the twist in the coil spring resulting in a tendency to form an initial crack, it can be stated that the coil spring had a fatigue fracture marked by the presence of beach marks.

5. References
[1] Prawoto Y, Ikeda M, Manville SK and Nishikawa A 2008 Eng. Fail. Anal. 15 1155-74.
[2] Putra TE, Abdullah S, Schramm D, Nuawi M Z and Bruckmann T 2017 Mech. Sys. Sig. Proc. 90 1-14.
[3] Putra TE and Husaini 2018 AIP Conf. Proc. 1983.
[4] Husaini, PutraTE and Ali N 2018 IJAME 15 5251.
[5] Putra TE and Husaini 2018 IOP Conf. Series: Materials Sciences and Engineering 352.
[6] Wahl AM 1884 Mechanical Springs (McGraw-Hill Book Company).
[7] Hayes M 2015 Tech-Spring Report 15 End Coil Failures (Institute of Spring).
[8] Callister W 2007 Materials Science and Engineering: an Introduction (John Wiley & Sons, Inc).
[9] Todinov MT 1999 Int. J. Mech. Sci. 41 357-70.
[10] Zhu Y, Wang Y, Huang Y 2013 Case studies in Eng. Fail. Anal. 2 169-173.
[11] Kosec L, Nagode A, Kosec G, Kovacevic D, Karpe B, Zorc B and Kosec B 2014 CSEFA 41 1-4.