Failure analysis of overrunning clutch spring for main transmission system of helicopter

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Abstract. In the present work, the premature rupture of a spring used in the aviation sprag overrunning clutch of the helicopter was analyzed based on the general method for failure analysis by use of the investigations of the fracture surface, mechanical and chemical performance as well as the microstructure of the spring material. The results showed that spring breakage is mainly caused by mechanical fatigue. The cracks and fracture originated from internal surface of the spring, and the cracks extended from outside surface of the spring toward the external surface of the spring, which was consistent with the direction of tensile residual stress on the internal surface of the spring. The marks of the shot peening were obvious on the outer surface, while the inner surface had obvious metal flow lines, indicating that the residual tensile stress formed on the internal surface of spring. Moreover, the oxide inclusions were also detected on the internal surface of spring. It can be noted that the stress concentration on the spring internal surface and oxide inclusions are responsible for the fracture of the spring.

1. Introduction
Sprag overrunning clutch is an important component for the transmission system of the helicopter, and it is a key part between the engine and the main gearbox, which ensure their engagement and disengagement. Energizing spring is an important part in the overrunning clutch, which is set at both ends of the sprags to ensure that all of the sprag cams contact the inner and outer race all the times (Figure 1). Thus, the sprag are always ready for engagement immediately. This is extremely important to ensure that the load is evenly distributed on all sprags when they engage with the inner and outer race [1].

![Figure 1. The contact schematic view of energizing spring with sprags.](image-url)
Among the various failure mechanisms of springs used in sprag overrunning clutch, fatigue failure is a very universal phenomenon. Cyclic stress is applied to sprag overrunning clutch during the fatigue performance test, in every cyclic, the torque increased from 0 to 1800Nm in 5s and consequently energizing springs bear a cyclic stress. The spring has failed after serving for 350 hours which is much lower than its expected life of 800 hours. Therefore, it was necessary to carry out a failure investigation of the energizing spring to determine the cause for failure. Generally, deficient microstructure or presence of stress concentration are the main cause of failures [2]. It is well known that inclusions have an effect on fatigue behavior, especially at high stress amplitude [3]. Surface residual stress is another factor known to all affecting fatigue performance [2]. Tensile stress promotes fatigue failure of surface, while compressive stress will improve the fatigue performance. Through proper stress relief treatment [4] or shot peening treatment, the influence of unfavorable residual stress on the surface can be reduced (compression stress applied to the surface). Although shot peening has been widely used in the industry, there are still problems and often need to optimize the process [5].

This paper introduces the procedure and results of failure analysis of the spring of the overrunning clutch with diagonal brace, so as to determine the cause of early fracture during service.

2. Investigation method

The geometric features of the analyzed spring and the chemical elements of the relevant steel were showed in Table 1 and Table 2, respectively. The processing process of the spring is as follows: fitter winding → shaping and tempering → shot peening.

Other paragraphs are indented (BodytextIndented style). The chemical composition of failed energized spring was analyzed by standard atomic absorption spectroscopy. Samples for optical microscope and scanning electron microscope (SEM) analysis as well as hardness measurement were prepared by standard metallographic specimen preparation technology. Nital (4%) was used as etchant to show the microscopic structure. Microstructure analysis and fracture morphology analysis were carried out using scanning electron microscope (SEM) of energy spectrum X-ray microanalysis (EDS). According to the American Society for Testing and Materials (ASTM) standards, an optical microscope was used to grade inclusions that are not metallographically corroded. The hardness was measured with a Vickers hardness tester.

| Table 1. Geometric parameters of spring test piece. |
|-----------------------------------------------|
| Average diameter (mm)                        | 2.95 |
| Wire diameter (mm)                           | 0.6  |
| Spring length unrestrained (mm)              | 300  |

| Table 2. Composition analysis of test spring steel (designation SH considering EN-10207-1). |
|-----------------------------------------------|
| element                                      | min. | max. |
| Carbon (%)                                   | 0.35 | 1.00 |
| Copper (%)                                   | 0    | 0.2  |
| Manganese (%)                                | 0.5  | 1.2  |
| Silicon (%)                                  | 0.1  | 0.3  |
| Phosphorous (%)                              | 0    | 0.035|
| Sulfur (%)                                   | 0    | 0.035|

3. Results and discussion

3.1. Visual examination

Observation of springs was carried out through optical microscope and scanning electron microscope (SEM). As shown in figure 2, The crack is perpendicular to the axis of the spring and there were no
obvious plastic deformation characteristics. The shot peening marks were obvious on the outside surface (Figure 3a), however the inner surface had obvious metal flow lines (Figure 3b). The difference in surface morphology between inside and outside was decided to shot peening process. During the winding process, the outside surface of the spring is subjected to tensile stress. After winding into a spring, the outer surface of the spring bears compressive stress, and the inner surface of the spring bears tensile stress [6].

The shot peening process is the last step of spring processing, shot peening acting on the outside surface of spring, however the inner surface bears a relative block residual stress. The cracks origin from the inner surface, and the opening direction of the spring is consistent with the residual tensile stress of the spring, so there may be a certain relationship between spring cracking and residual stress.

![Figure 2. Appearance of the spring fracture.](image)

![Figure 3. Morphology of the spring surface (a) the outer surface (b) the inner surface.](image)

3.2. Fracture observation

The spring was observed with a scanning electron microscope. The fracture is composed of two areas, region 1 is even fracture, close to the inside surface of spring; region 2 is relatively rough, and the height difference is large, called slanted fracture, as shown in Figure 4a. As can be seen from Figure 4b, the even fracture is flat of the spring. Fracture zone 1 accounts for approximately 60% of the cross section of the spring. Region 2 can be observed with fine dimples and other morphologies, as shown in Figure 4c.
According to morphology of even feature, fracture and cracks started from the inside surface of the spring and extend radially to the outer surface. The results showed that the spring fracture is caused by mechanical fatigue [6].

![Image](image1.jpg)

**Figure 4.** (a) Fracture occurring in spring (b) Even fracture in region 1 (c) Slanted fracture in region 2.

### 3.3. Chemical analysis

Chemical analysis was carried out from the failed spring. The chemical analysis results are given in Table 3. It was observed that the chemical composition is in accordance with EN-10270-1. The chemical analysis shows that chemical composition is not the cause of premature of the energizing spring.

| sample | C   | Si  | Mn  | S    | P    | Cu  | Fe    |
|--------|-----|-----|-----|------|------|-----|-------|
| spring | 0.72| 0.23| 0.53| 0.008| 0.012| 0.05| balance|

### 3.4. Metallographic examination

A fracture section was taken from the spring below the fracture surface. Microstructure as shown in Figure 5a and Figure 5b was sorbite, which was the normal microstructure for this grade of steel.

Figure 6a is an optical micrograph of a polished but unetched surface, there are some inclusions, from the center to the edge of spring wire, the number of inclusions increases. This was expected because during processing, foreign non-metallic inclusions are usually separated in the central area, EDS determined the elemental properties of inclusions as silicon, sulfur, aluminum, calcium, potassium and oxygen [7] (see Figure 6b). The metallographic examination shows that oxide inclusions may contribute to the premature of the energizing spring.

![Image](image2.jpg)
Figure 5. Optical micrographs the inner surface of the coil near the break under corrosion conditions (a) perpendicular to the axis of the spring (b) parallel to the axial direction of the spring.

Figure 6. (a) Optical micrograph on the longitudinal section near the polished but unmatched fracture surface, showing the oxide inclusions at 100X (b) Electron microscopy and energy spectrum analysis of inclusions related to the origin of fracture.

3.5. Vickers hardness measurements
Table 4 shows the test results. The hardness of the material after thermomechanical treatment of the spring is uniform. The Vickers hardness measurements shows that Vickers hardness measurements is not the cause of the premature of the energizing spring.

| Reference                     | HV0.5 hardness | Average HV0.5 Hardness |
|-------------------------------|----------------|------------------------|
| Spring zone near the failure  | 608.2          | 617.5                  |
|                               | 625.9          |                        |
| Spring zone far from the failure | 618.6        | 614                    |
|                               | 603.1          |                        |

4. Conclusions
Based on the results of the experimental analysis performed on the spring fragment, it can be concluded that the fracture of the spring was caused by a mechanical fatigue mechanism, even fracture accounts for about 60% of the spring cross section. The residual tensile stress on the spring inner surface and oxide inclusions are the main reason for the fracture of the spring.
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