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A STUDY ON FAILURE MODES OF LOCOMOTIVE SUSPENSION COIL SPRING

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ABSTRACT

This paper is discussion about automotive suspension coil springs, their materials characteristic, manufacturing and common failures. An in depth discussion on the parameters influencing the quality of coil springs is also presented.

A coil's failure to perform its function properly can be more catastrophic than if the coil springs are used in lower stress. As the stress level is increased, material and manufacturing quality becomes more critical. Material cleanliness that was not a major issue decades ago now becomes significant. Decarburization that was not a major issue in the past now becomes essential. To assure that a coil spring serves its design, failure analysis of broken coil springs is valuable both for the short and long term agenda of locomotive manufacturer and parts suppliers. This paper discusses several case studies of suspension spring failures. The failures presented range from the very basic including insufficient load carrying capacity, raw material defects such as excessive inclusion levels, and manufacturing defects such as delayed quench cracking, to failures due to complex stress usage and chemically induced failure. FEA of stress distributions around typical failure initiation sites are also presented.

Keywords: Coil spring, Fatigue, Penning, Residual Stress

INTRODUCTION

A mechanical spring is defined as an elastic body which has the primary function to deflect or distort under load, and to return to its original shape when the load is removed. Springs are used in mechanical equipment with moving parts, to absorb loads, which may be continuously, or abrupt varying. The absorption of the loads takes place in the form of elastic energy. Coil springs are manufactured from rods which are coiled in the form of a helix. The design parameters of a coil spring are the rod diameter, spring diameter and the number of coil turns per unit length. Normally, springs fail due to high cycle fatigue in which the applied stress remains below the yield strength level and the loading cycle is more than 10^5 cycles/sec. In springs made from steels, the chemical composition of the steel and the heat treatment given to it are such that the inherent damping capacity of the steel is high. It is rare that a spring fails in service due to faulty design. The causes of failures are mainly related to deficient microstructure and/or presence of stress concentration raisers. A common microstructure in steel springs is tempered martensite with certain specified hardness range which is tailored during manufacturing practice. Among the stress raisers on the surface; roughness of the surface and inclusions are two important examples. The adverse effect of inclusions on fatigue behaviour is well known. Their effect is more pronounced at high stress amplitudes [1]. Residual stress on the surface is another well known factor for influencing fatigue behaviour. Tensile stress at the surface promotes fatigue failure, and compressive stress improves the fatigue behaviour. The effect of adverse residual stresses on the surface can be reduced either by proper stress relief treatment [2] or by giving a shot peening operation, which imparts compressive stress on the surface.

Although shot peening is extensively employed in the industry, problems are still encountered and optimization of the process is often required [3]. In this paper, the failure modes of a suspension coil spring of locomotive which failed only after a few running distance is discussed. Though discussions on the causes of failure of springs are available in the literature, the present case deserves attention since it was not apparently caused by fatigue – the usual mode of failure for a spring.

Major Imperfections in Coil Manufacturing

Raw material selection is always the most important decision in obtaining the best quality of any product, including coil springs. The selection of the raw material usually includes the enforcement of cleanliness, microstructure, and decarburization inspection. Other sources of defects include improper heating patterns prior to coiling. The control of the prior austenite grain size is an important step in coil manufacturing. Fig.2 shows the difference between a small grain size and a large grain size. This example was taken from identical materials processed with different parameters. Although not reflected by other mechanical properties, except by metallography when interpreted by an expert, larger prior austenite grain size is proven to have less advantage in fatigue life than that of small size. Once the raw material is heated properly, the coil is usually formed. Physical defects due to coiling sometimes cause the coil to fail early. Following coil formation, a heat treatment process is performed by means of quenching, followed by tempering. Heat treatment related defects are another major cause of the coil failing early. These defects include, but are not limited to, quench cracking, insufficient tempering, and overtempering. After tempering, the coil spring is shot peened. The shot peening process is beneficial for two reasons: it cleans the surface of defects and scale caused by quenching, and introduces compressive residual stresses at the surface.. After setting, coating is typically the last step of coil making. The process of coating consists of two major steps: pre-treatment and coating application. The main ingredient in the pre-treatment is usually zinc.

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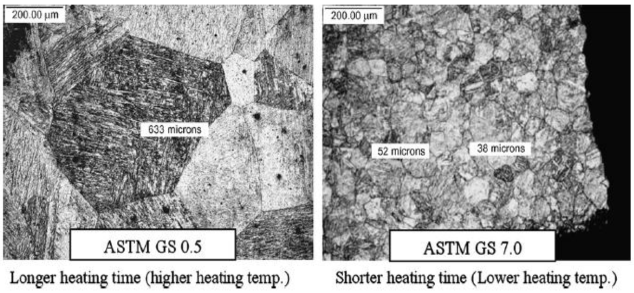

Fig. 2. Identical raw materials heated with different heating patterns. on the left, the prior austenite grain size is clearly larger than that of the right.

CAUSES OF FAILURES

Raw Materials Defect

A typical raw material defect is the existence of a foreign material inside the steel, such as non-metallic inclusions.

In general, there are two types of foreign materials that can become trapped inside the steel solution: large imperfections such as spinells, and smaller imperfections such as inclusions that are caused by alloying elements. Fig.3 shows a raw material defect that is usually very difficult to find after a coil is formed. This type of defect is easy to detect during the cold drawing process of coil manufacturing preparation. An ideal raw material has the form of ferrite pearlite. However, a raw material can also have local bainite inside the ferrite pearlite matrix. Due to a hardness difference, such raw materials may exhibit internal cracking.

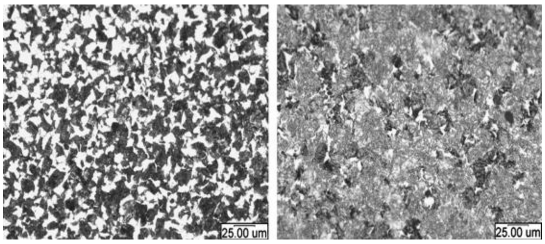

Fig.3. Appearance of different microstructures extracted from the same bar. on the left side, the microstructure is normal ferrite pearlite. on the right side, the same material has bainite structure inside the ferrite pearlite matrix

Surface Imperfections

Surface imperfections can occur as small hardening cracks, tool marks, scale embedded to the base material during cold drawing, or surface flaws inherited by the raw material. Poorly shot peened surfaces can also be classified as surface imperfections. Fig.4 shows a comparison between two different coils that failed at similar locations, but possessed completely different fatigue lives. On the left side, the surface was shot peened poorly and therefore exhibited a shorter life. On the right side, the surface was shot peened sufficiently and therefore had a longer life. An example of a small quench crack that can be classified as a surface imperfection In this case the heating process and the heat treatment itself were not wrong, however, the quench oil was contaminated with water, causing an extremely high cooling rate locally. Similar to a quench crack, a delayed crack can also sometimes occur. This could be caused by either insufficient tempering time or temperature, or by prolonged time between quenching and tempering.

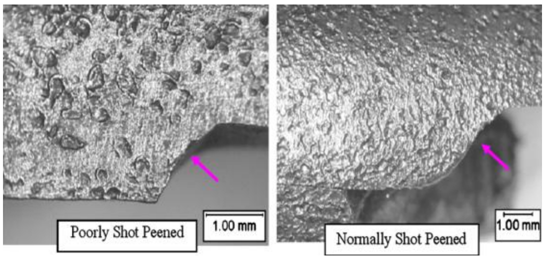

Fig.4. Surface imperfections due to poor shot peening condition

Improper Heat Treatment

Improper heat treatment can be easily overlooked since a temperature difference in heating does not relate directly to the hardness of the material. Extensive evaluations are usually needed to identify this problem. Fig.2 shows a typical example of an improper heat treatment. Prolonged heating can cause the prior austenite grain size to grow significantly. Improper heat treatment can also result in the microstructure becoming pearlite instead of the required martensite. This type of defect is easier to identify due to the clear difference in hardness. Fig.5 shows two different coils of the same product with varying microstructure. This defect usually occurs when the heating system does not operate normally. Again, referring to the figure, the left hand side coil has a much lower lifetime than that of the right side. Tempering induces the decomposition of the retained austenite into mixture of ferrite and carbides

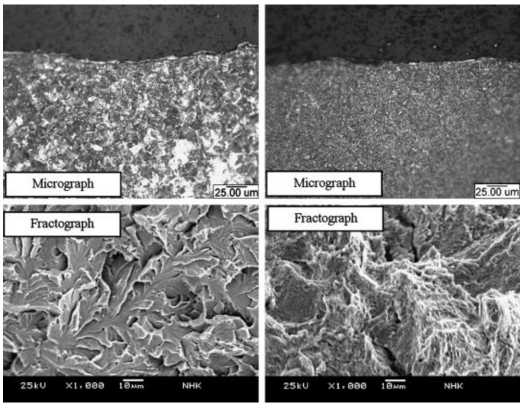

Fig.5. Improperly heat treated sample (left) vs. properly heat treated sample (right).

Corrosion

Corrosion is a more common cause of spring breakage than is usually understood by users; however, recent coating technology has reached a point where it is able to protect the metal from even the hardest cold stone chipping. Fig.6 shows the appearance of a coil which failed due to corrosion. The right side of the figure depicts the cross section of the corresponding coil, with the 1 line illustrating its approximate original dimension.

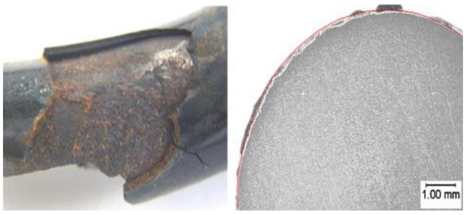

Fig.6. Coil spring which broke due to corrosion

ANALYSIS

Procedure

A finite element analysis was performed to check the local stress distribution around a given defect using a typical coil spring. First, the overall stress distribution was checked without any defect in the material, and then at the location where the highest stress was found, each defect was added. Since the size of the defect is significantly smaller than the whole model, a sub modeling technique [4] was used. This technique is used to study a local part of a model with refined meshing based on the FEA result of a global model with coarse meshing. Boundary conditions for the sub model will be automatically interpolated from the global model solution. As shown in Fig.7, the sub modeling technique was used twice for this study. Sub model 2 was modified to apply various defects. For meshing, either the quadratic brick element (C3D20) or quadratic tetrahedron (C3D10) was used. For material specifications, typical spring steel properties, E = 210 GPa and m = 0.3, were used except for the decarburized layer. The commercially available FEA software, ANSYS, was used here to study each stress distribution.

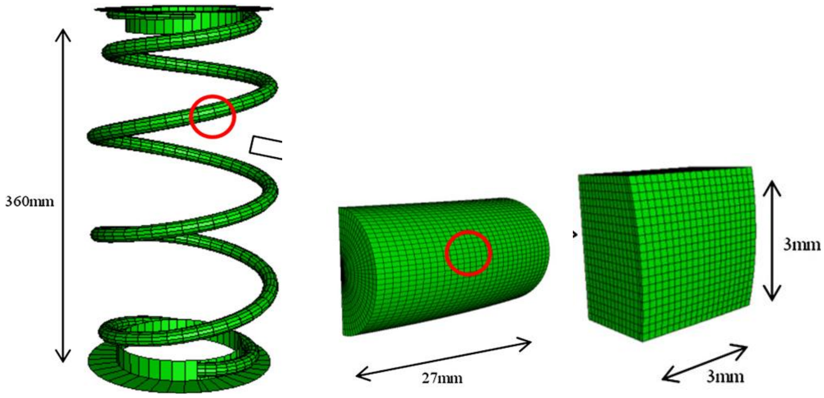

Fig.7. FEA model of a coil spring and its sub models

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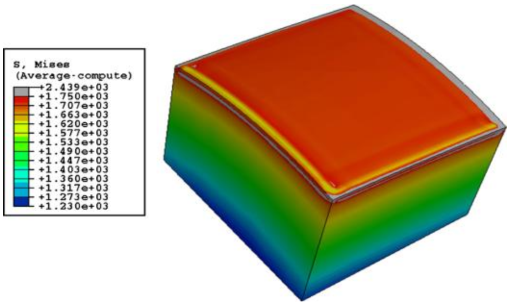

Fig.8. Von Mises stress result of no-defect model

FEA Result of Model without Defect

For comparison with the defect model, Sub model 2 was analyzed first without any defects. Boundary conditions were interpolated from the result of Sub model 1 to the inner and side surfaces of Sub model 2. Fig.8 shows the Von Mises stress distribution. The highest stress was found at the outer surface and the lowest at inner side of wire. The highest Von Mises stress was about 1715 MPa, which matches the stress level of the global model. The gray area around the outer edge shows a stress concentration, however this is ignored since it is where the boundary condition was applied.

DEFECT IN FEA MODELS AND RESULTS

Inclusion

A cubic hole was placed about 1 mm below the outer surface; its size is 50 µm (Fig.9, red dot is the inclusion). Instead of using a foreign material for the cubic area, it was left as a hole for simplification. Since a higher stress concentration was expected around the inclusion area, a finer mesh was used at the center and coarser mesh was used at the outer area (Fig.9b). The stress distribution is shown in Fig.10. As expected, a local stress concentration is observed at the inclusion area, and the highest Von Mises stress reached 2000 MPa, which is higher than the outer surface stress level. Stress on other areas, such as outer surface, was at the same level as the no-defect model.

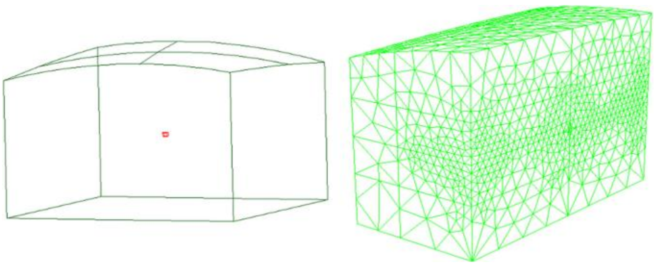

Fig.9. Part model with inclusion. (Left), FEA model with inclusion (display model is cut in half to show inside) (right)

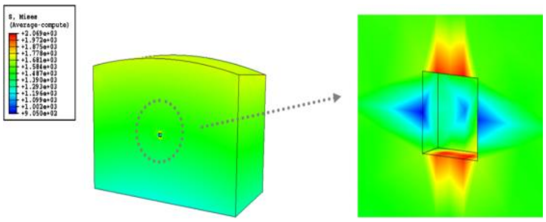

Fig.10. Von Mises stress result of inclusion model.

Imperfection

A model was created based on a crack on outer surface of spring, the surface imperfection is inherited from the raw material. A crack (50 µm width, 500 µm depth) alongside of the centerline of the wire was applied to the Submodel 2 as shown in Fig.11. The stress distribution is shown in Fig.12. A high stress concentration is observed at the crack location, and the Von Mises stress exceeded 4000 MPa, which is much higher than the outer surface stress level. Therefore, the product would likely fail from this point. A stress concentration is also observed at the vertical edge, however this concentration occurred due to the boundary condition and should be ignored.

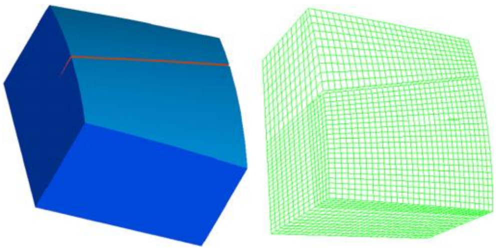

Fig.11. Part model with imperfection (Left) and its FEA model (right)

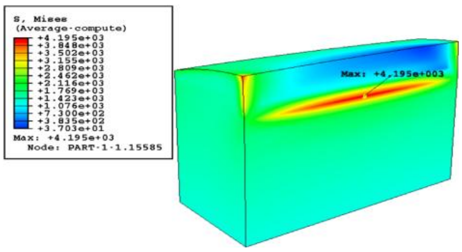

Fig.12. Von Mises Stress result of imperfection model (display model was cut at crack location)

Corrosion

Instead of modeling the actual corrosion part, a simple oval shape was removed from the outer surface to simplify the FEM model. Its size is approximately 300 µm in depth, 500 µm in height, and 1mm in width. Finer meshing was used around the corrosion area since a higher stress concentration was expected there. The model is shown in Fig.13. The stress distribution is shown in Fig.14.As expected, a local stress concentration is observed at the

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bottom edge of the corrosion area, and its Von Mises was about 3450 MPa, which is again much higher than the outer surface stress level. This high stress concentration will cause early spring breakage from this point.

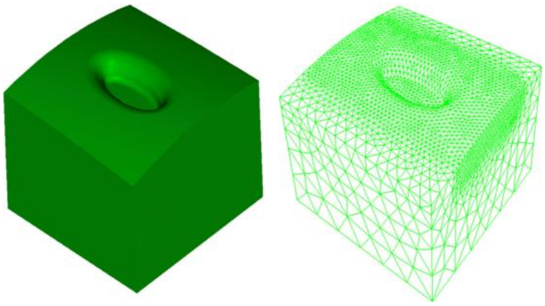

Fig.13. Part model with corrosion (left) and its FEA model (right)

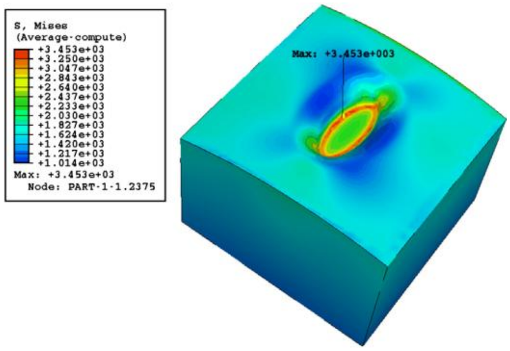

Fig.14. Von Mises stress result of corrosion model

CONCLUSION AND RESULTS

Table I shows the summary of analysis results. As expected, a local stress concentration was observed in the inclusion, imperfection, and corrosion defect models at each defect area, and those stress values were much higher than the model without any defects. These high stress concentrations will cause an early failure; hence the material needs to avoid these defects as much as possible.

Table 1. FEA Summary

Defect	Summary
None	No stress concentration. The highest stress was found on the outer surface. Von Mises stress = 1715 MPa. Max.Principal stress = 1200 MPa. No plastic deformation occurred.
Inclusion	Stress concentration is observed at the inclusion area. Von Mises stress = 2069 MPa. Max.principal stress = 1922 MPa.
Imperfection	Stress concentration is observed at the crack location. Von Mises stress = 4195 MPa. Max. principal stress = 2670 MPa.
Corrosion	Stress concentration is observed at the bottom edge of corrosion surface. Von Mises stress = 3453 MPa. Max.principal stress = 3286 MPa.

Failure analyses of locomotive suspension coil springs were performed and summarized in this paper. Subsequently, finite element analyses of representative cases were also modeled. Integrating finite element modeling in metallurgical failure analysis synergizes the power of failure analysis into convincing quantitative analysis. This presumably will be the trend in failure analysis.

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