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FAILURE ANALYSIS OF LOCOMOTIVE SUSPENSION COIL SPRING USING FINITE ELEMENT ANALYSIS

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ABSTRACT

This paper is a discussion about locomotive suspension coil springs, their fundamental stress distribution, materials characteristic, manufacturing and common failures. Investigation on the premature failure of suspension coil spring of a locomotive, which failed within few months after being put into service, has been carried out analytically and using FEA software. Besides visual examination, other experimental techniques used for the investigation were (a) instrumental chemical analysis on spectrometer, (b) design calculation for finding factor of safety, (c) calculate and compare design stress and ultimate stress of spring, and (d) calculation of bogie springs with sharing load. Inherent material defect in association with deficient processing led to the failure of the spring.

Keywords: Coil spring, Fatigue, Penning, Residual Stress.

INTRODUCTION

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. 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 or by giving a shot peening operation, which imparts compressive stress on the surface.

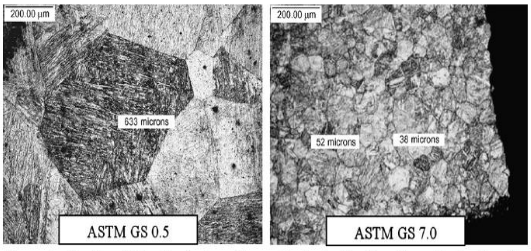
Although shot peening is extensively employed in the industry, problems are still encountered and optimization of the process is often required. In this paper, the failure of a suspension coil spring of locomotive which failed only after a few 3-12months of running instead of 4.5 years is discussed. 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.

The present failure analysis was carried out on the failed spring rod shown in Fig.1. The diameter of the spring was 104 mm and that of the spring rod 16.5 mm. The steel grade for the spring was ***50CrV4***.

Figure 1. Photograph of failed coil spring having fracture surface.

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.



Longer heating time (higher heating temp.) Shorter heating time (Lower heating temp.)

Figure 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.

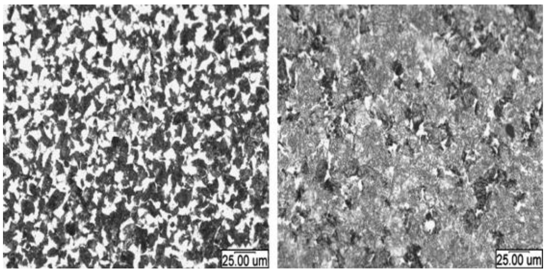


Figure 3. Appearance of different microstructures extracted from the same bar. on the left side, the microstructure is normal ferrite pearlite. on the right side, the same material has bainite structure inside the ferrite pearlite matrix.

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.

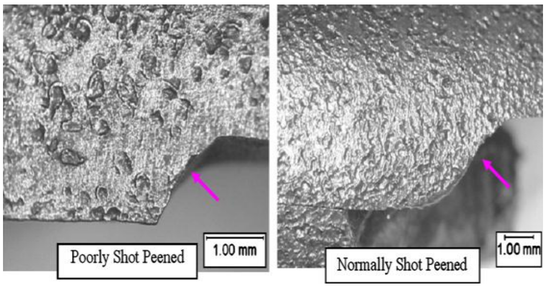


Figure 4. Surface imperfections due to poor shot peening condition.

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

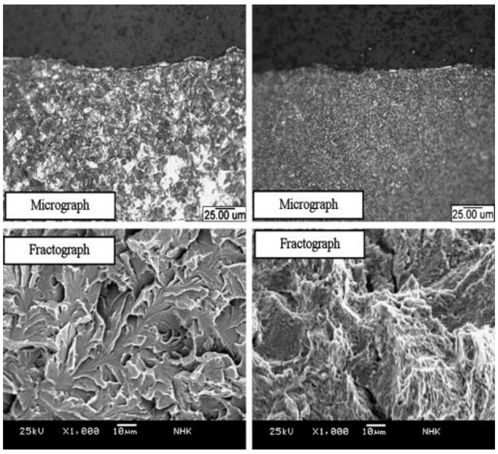


Figure 5. Improperly heat treated sample (left) vs. properly heat treated sample (right).

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.

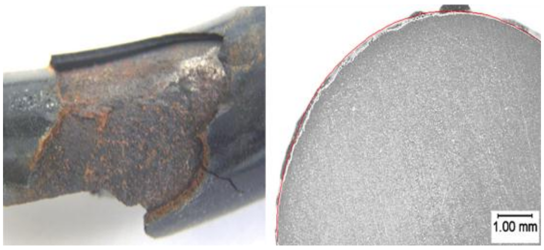


Figure 6. Coil spring which broke due to corrosion.

Mathematical Calculations for Spring

Analytical study of failures of primary helical springs of middle axle of locomotive with proposed modifications to improve their stress parameters.

1. Even after implementing all the existing standard maintenance practices, the failure of inner primary springs of middle axle has not been arrested. Moreover, the chemical analysis of failed springs found to be within standard permissible limits. Table 1 shows that about 80% of cases of failures belong to primary inner springs.

Table 1. Number of failures in springs

Year	End axle	Middle outer	Middle Inner	Total
Year-(1)	5	4	41	64
Year-(2)	3	8	51	70
Year-(3)	1	3	25	33

2. To find out the solution of the problem, an analytical study of load factors of springs has been done by following ways:

A. Analytical results by applying load on individual spring

After doing analytical calculations, it is observed that the solid shear stresses are more than ultimate shear stress in case of locomotive springs. The same can be shown in the table 2:

Table 2: Shear stresses by applying individual load on each spring

SN	Location of spring	Shear stress	Std limit	Remark
01	Middle outer spring	981 N/mm^2	< 860 N/mm^2	More than limit.
02	Middle inner spring	1010 N/mm^2	< 860 N/mm^2	
03	End axle spring	1025 N/mm^2	< 860 N/mm^2	

B. Analytical results by applying sharing load on

During actual working conditions the solid stress is not achieved because the spring is not compressed fully to solid height.

The loading pattern in locomotive is such that the height of middle axle outer spring is 258.6 mm and middle axle inner spring is 252.4 mm. Thus the load is first shared by middle axle outer spring then middle axle inner spring. Thereafter the load is taken by end axle spring after compression of 20 mm as the free height of end axle spring is only 238.8 mm.

Thus under static condition when the loco body is lowered on the bogie the shear stress, shown in table 3

Table 3. Shear stresses by applying sharing load on each spring

SN	Location of spring	Static Shear stress	Remarks
01	Middle axle outer spring	599 N/mm^2	More
02	Middle axle inner spring	**611** N/mm^2	**More**
03	End axle spring	547 N/mm^2	More

3. From the above table, it can be seen that static stress on springs of locomotive is more than ultimate stress. The stress is maximum in the middle axle inner spring.

The static shear stress is described below:

Static Shear Stress = $K \times 8 \times W \times D / (\pi d^3)$

Where, K is WAHL's factor

= {(4C-1) / (4C-4)} + [0.615/C]

D is mean diameter of spring

W is static load

d is bar diameter of spring

C is spring index = D/d

To reduce shear stress in the springs, the bar diameter, the mean diameter & spring Index, C=D/d have to be designed in proper way.

CONCLUSION AND RESULTS

Long Term Modification

This involves increase in outer diameter, bar diameter and number of active coils of middle axle primary outer and inner spring, shown in the table 4:

Table 4. Proposed dimensions for spring.

Sr. No.	Parameter to be changed	Existing	Proposed
1.	**Outer spring**		
A	Outer diameter	212 mm	221 mm
B	Bar diameter	31.5 mm	36 mm
2.	**Inner spring**		
A	Outer diameter	104 mm	110 mm*
B	Bar diameter	16.5 mm	18 mm
C	No. of active turns	7.5 coils	8 coils

Table 5: Shear stress for proposed dimension of inner spring

SN	Location of spring	Static shear stress	
		Existing	Proposed
01	Middle axle outer spring	599 N/mm^2	**433** N/mm^2
02	Middle axle inner spring	**611** N/mm^2	**366** N/mm^2
03	End axle spring	547 N/mm^2	--

It requires increase in bore diameter of inner coil insulating base by 3mm, which can be done by machining.

Analytical study reveals that, after increase in bar diameter and other parameters as above, the static shear stresses on primary springs are found to be less as well in the range. This can be shown in table (5):

The shear stress in the spring has come down considerably with the increase in bar diameter & mean diameter. The springs can be accommodated in the existing axle box and only minor work involved is to cut the inner coil insulating base by 3 mm.

Simultaneously, keeping in view of better mechanical properties to steels with molybdenum as an additional alloying element, the spring steel grade 51CrMoV4 may find more suitable than existing grade 50CrV4.

Short Term Modification

During study, it has also been observed from the drawings, that the free height of the end axle spring is less than that of middle axle outer spring by 20 mm. Due to this and as explain in para-B above, the load is being shared first by middle axle springs than end axle springs, the breakages of middle axle springs are more especially inner spring because of its lesser bar diameter. It is noted from above table that stress is more on middle springs than end axle spring.

To minimize the difference between free height of middle & end axle springs it is proposed to increase the free height of end axle springs by putting flat solid metal plate (shim) of 5 mm under end axle springs so that the load of middle axle coil will be shared by end coils equally. The load distribution after the provision of shim is shown in table 6:

Table 6. Load distribution after the provision of shim

Shim thickness (mm)	**Static stresses (N/mm^2) on springs**		
	Middle outer	**Middle inner**	**End**
0	**599**	**611**	**547**
4	570	585	560
5	**565**	**578**	**563**
6	559	565	566

Thus, it can be seen that with the provision of shim in end axle, the stress in middle axle inner spring has come down from 611 to 578 mm and in end axle has increased from 547 to 563 mm, which is the average range.

ANALYSIS RESULTS

An analysis results found at loading condition in which base face is fixed and load acting on the top face of the component is 9300N.

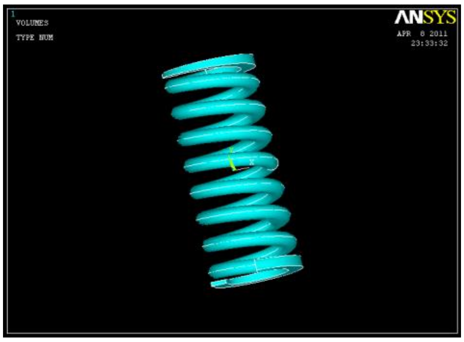


Figure 7. CAD model of spring

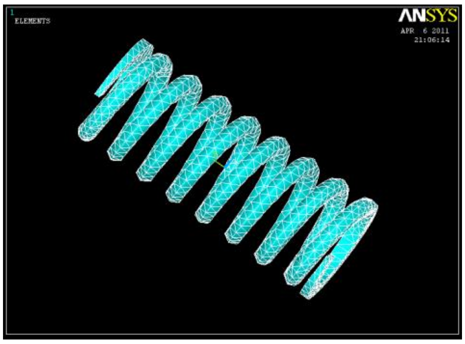


Figure 8. Meshing of spring.

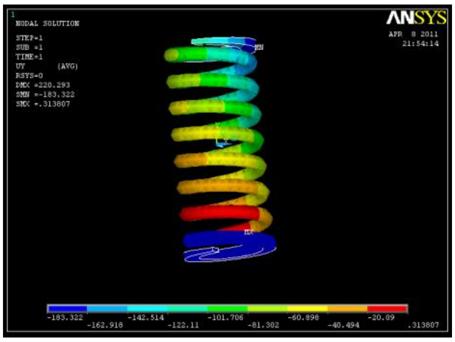


Figure 9. Deformation at 9300N load acting on the Spring when base is fixed

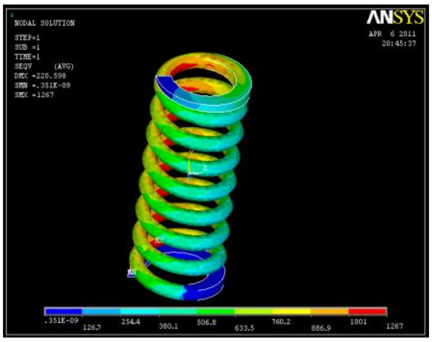


Figure 10. Von mises stresses at 9300N load acting on the spring when base is fixed

CONCLUSION AND RESULTS

The static analysis of locomotive suspension coil spring is carried out to find out the deformation in loading conditions and it is found to be 0.313807MM^{max} in y-direction.

The stress induced in spring due to loading conditions .The values obtained from the FEA analysis is 1267 Mpa. And theoretical stress is 1010 Mpa, but permissible stress value of spring is 860Mpa therefore the design is unsafe.

The value of stress found to be more at the critical section of the spring as indicated by red colour. Hence possibility of failure is more at that section compared to other section of spring.

Computer Aided design Model of spring was prepared on PRO/E Wildfire4.0 and it was analyzed in ANSYS10.0 software to find out Nodal solution and Von mises stress acting on the spring.

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