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Premature fracture in automobile leaf springs

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Abstract

In this work, the origin of premature fracture in leaf springs, used in Venezuelan buses, is studied. To this end, common failure analysis procedures, including examining the leaf spring history, visual inspection of fractured specimens, characterization of various properties and simulation tests on real components, were used. It is concluded that fracture occurred by a mechanism of mechanical fatigue, initiated at the region of the central hole, which suffered the highest tensile stress levels. Several factors (poor design, low quality material and defected fabrication) have combined to facilitate failure. Preventive measures to lengthen the service life of leaf springs are suggested.

Keywords: Leaf springs; SAE 5160 H steel; Fatigue

1. Introduction

Multi-leaf springs used as suspension components in some Venezuelan buses were found to fail after a short service time. Spring fractures caused no damage in other structural components of the buses or accidents of any kind. However, nearly 60 spring units had to be withdrawn from market.

As can be seen in Fig. 1, the studied springs were of the semi-elliptical type and consisted of six steel leaves of which four served as major leaves and two as secondary leaves. This suspension component is connected at both ends with the bus chassis and rests on the wheel axle. Some mayor leaves fractured within six months of service.

In this work, the origin of premature failure in the springs is investigated. To this end, common failure diagnosis methods [1,2] involving examination of manufacturing and failure histories, macroscopic inspection, chemical analysis, metallographic analysis, hardness measurements, static loading tests and fatigue tests, were employed. Various potentially effective remedial actions are proposed.

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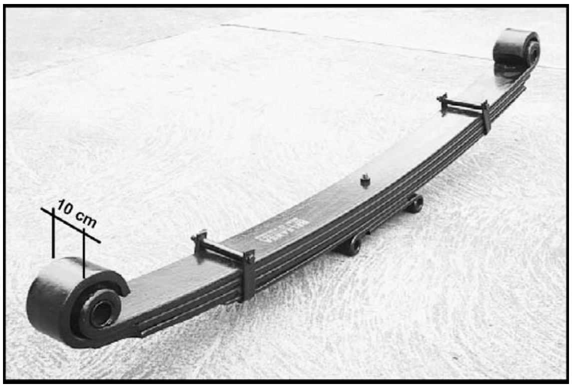

Fig. 1. Visual appearance of the leaf spring.

2. Spring history

The studied spring model was installed in 50-seat buses and subject to fluctuating loads and environmental conditions typical of an urban bus. The service conditions were thus the usual for this type of mechanical suspension component.

The spring manufacturing process, which is conducted entirely in Venezuela, starts from 102 mm wide × 15.88 mm thick sheets of SAE 5160 H steel obtained by hot rolling. Essentially, it involves cutting, forming and punching of the leaves, hardening by quenching and tempering, surface finishing by shot peening, and assembly of individual leaves by inserting a bolt through their central hole and fastening them, at the ends, with two clamps.

3. Macroscopic inspection

The studied spring was subject to visual and macroscopic inspection with a magnifier. The photograph of Fig. 2 is a plan view of the fracture, which occurred in the second leaf after six months of service. The fracture started at the central hole, in a plane normal to the leaf major axis, with no evidence of a prior plastic deformation. Fig. 3 shows the appearance of the fracture surface.

Morphologically, the fracture surface was typical of fatigue failure [3]. Thus, it consisted of a smooth region exhibiting ring marks extending into the crack origin on both sides of the hole and spanning nearly one half of the fractured area. The remaining material which was unable to withstand the service loads had suddenly broken by effect of overloading. The crack propagated normally to the main axis of the spring leaf. In summary, the fractographic evidence was typical of fatigue fracture. Also, the marks observed suggested that the crack originated in the vicinity of the top corner of the hole front (see Fig. 3); this was a region concentrating a high stress owing to its high and low relief, which, as expected, had reduced the fatigue strength of the material [4].

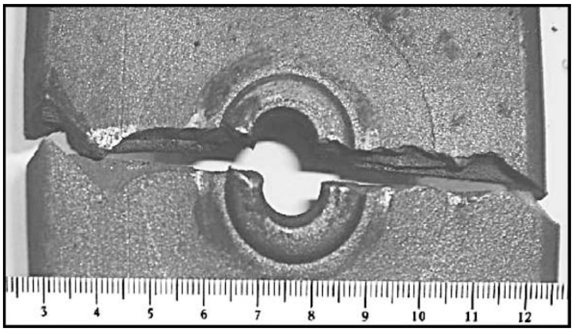

Fig. 2. Photograph of the fractured second leaf of a specimen which failed during service.

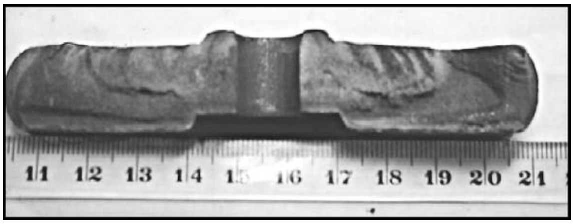

Fig. 3. Photograph of the fracture surface in the second leaf.

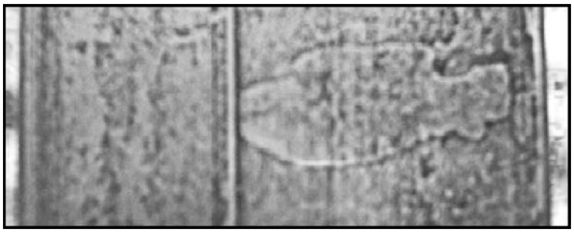

Fig. 4. Surface (tensile side) of a leaf exhibiting rolling lines and scabs.

Fig. 5. Fibering in the hole surface of a fractured leaf.

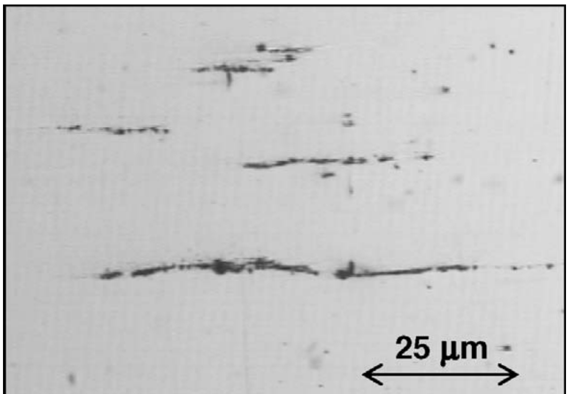

Fig. 6. Large aligned inclusions in the starting as-rolled steel sheet.

In addition, the leaves exhibited surface defects on both their outer sides and the hole inner side. Fig. 4 illustrates the condition of the surface of the first (master) leaf in a spring representative of a production batch. As can be seen, the leaf exhibited surface discontinuities in the form of scabs and rolling marks.

As can be seen in Fig. 5, the fractured springs also exhibited parallel deformation lines (fibering) in the thickness direction on the hole surface. This surface unevenness was a result of hot piercing with a punch during the manufacturing process. All these surface defects detract from fatigue strength [4]. Moreover, the steel was unclean (Fig. 6). The amount and size of inclusions were higher than it is recommended in current practice. This is especially harmful for fatigue resistance.

4. Chemical analysis

Specimens of service leaves were analysed for chemical composition of the surface and core, using a Spectrolab M5 optical emission spectrometer. The composition results were as follows:

(a) *Core*: Fe-0.64%C-0.73%Cr-0.83%Mn-0.22%Si-0.013%S-0.001%P-0.19%Cu, and traces of other elements.
(b) *Surface*: Fe-0.48%C-0.73%Cr-0.83%Mn-0.24%Si-0.013%S-0.001%P-0.21%Cu, and traces of other elements.

Based on these results, the springs consisted of SAE/AISI 5160 H (or UNS H51600) steel. However, the C content was lower on the surface than on the inside (0.48% versus 0.64%); this can be ascribed to decarburization during the whole manufacturing process – the preliminary hot rolling step included. In fact, surface decarburization in leaves is known to reduce the fatigue strength of steel [4].

5. Metallographic analysis

Specimens for metallographic analysis were prepared according to ASTM E3 standard. After surface preparation, the material was etched with Nital for microscopic inspection. Particularly, fractured specimens, i.e., in the quenched and tempered condition, were examined. Usually, steel is quenched from 860 °C by cooling in oil at 50 °C, and tempered by heating at 490 °C for 45 min.

The micrograph of Fig. 7 shows the region adjacent to the fracture in a broken specimen in a lengthwise section normal to the rolling surface (Orientation E in ASTM E3 standard). In addition to the tempered martensite structure, which is typical of the quench-and-temper condition, the material exhibited islands of ferrite, which is the white constituent. This microstructure is consistent with a deficient quenching of the material.

The presence of ferrite, which is a soft constituent, can considerably reduce the fatigue limit [5].

In order to more precisely assess the efficiency of the industrial quenching operation during the manufacturing process, a quenched leaf was also metallographically examined under the above-described conditions.

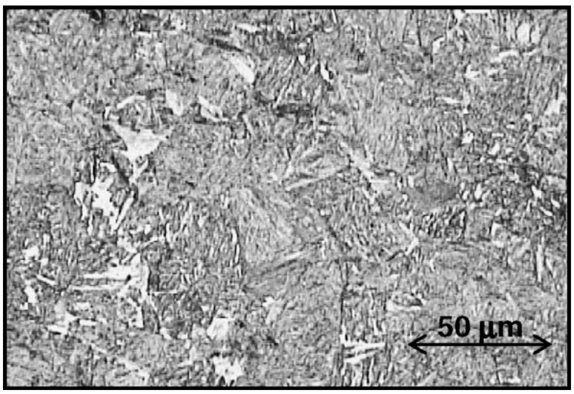

Fig. 7. Micrograph of a zone in the vicinity of the fracture surface, taken in the E orientation.

The as-quenched structure is not fully martensitic; rather, the leaf microstructure exhibits a number of scattered white spots revealing the presence of retained austenite. Both retained austenite and its tempering products are softer than tempered martensite and have an adverse effect on fatigue strength. Nevertheless, proeutectoid ferrite was not observed in this sample. These results point out that the quenching operation is not very reliable.

The amount of retained austenite additionally depends on the chemical composition of the particular steel, the austenization temperature and time, and the cooling rate. The austenization time is typically 1 h per inch thickness. The austenization temperature is very important inasmuch as it can alter the amounts of carbon and alloy elements dissolved by austenite, which in turn influence that of austenite ultimately retained. Also, keeping austenite hot, especially during cooling, tends to retard its transformation into martensite. The specific manufacturing process for the studied spring involves a relatively high quenching temperature (860–890 °C) compared to the recommended value, which is 800–845 °C [6]. Also, the transfer of leaves from the furnace to the oil bath at the production plant was found to take a rather long time (*ca.* 12 s). In addition, the bath temperature, 70–80 °C, exceeded the recommended levels. All these factors resulted in slower cooling of the steel and in the formation of a possibly weaker material structure as a result. The fact that the quenching oil exceeded the recommended temperature may have resulted from being too old (aged) and containing sludge and tar deposits, which can clog the coolers thus reducing the efficiency of the entire quenching system [7]. Some authors [8] recommend that the temperature of the oil bath should be kept at about 40 °C.

One additional way of ensuring that quenching will produce an actually martensitic structure would be by replacing the spring material with SAE 4161H steel, which, unlike that used with the failed springs, contains 0.30% Mo, and has a better hardenability.

6. Hardness measurements

Specimens were subjected to Brinell hardness (HB) measurements in accordance with ASTM 110 and Rockwell C hardness (HRC) measurements following ASTM E18. HB measurements were made by using a hardened steel ball 10 mm in diameter, as indenter, and a load of 3000 kgf. The ball was used to repeatedly indent the convex surface of a fractured master leaf at 10 mm intervals from the centre to one end. The average hardness thus obtained was 397 HB; however, the measured values were rather disperse and some as low as 364 HB. This suggests the occurrence of uncontrolled local heating of the spring – and the resulting decarburization and softening at some points – during the manufacturing process. Also, the average hardness obtained, 397 HB, was somewhat lower than the recommended minima in the Japanese standard JASO C 601 (401–425 HB) and the SAE design manual [9] (415–461 HB). In addition, 397 HB is lower than the typical hardness of parabolic leaf springs (450 HB), which are made from the same material as the studied springs [10].

Rockwell C hardness (HRC) measurements were also made in the vicinity of the crack in specimens of a fractured – and hence quenched and tempered – leaf, as well as in leaves at the manufacturing stage, either

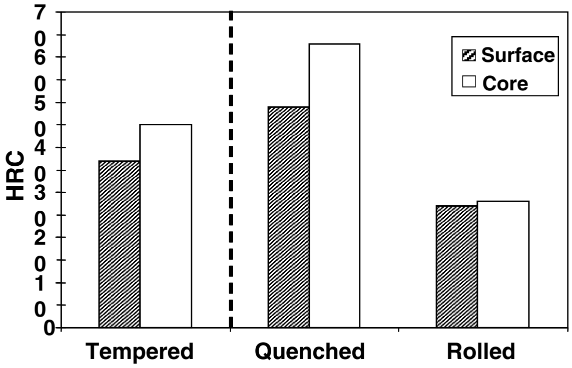

Fig. 8. Hardness of the fractured region – tempered – as opposed to that obtained after quenching and hot rolling.

in the as-rolled (as-received) or quenched condition. Measurements were made at both the surface and core of each leaf.

As can be seen in Fig. 8, the HRC value for the fractured specimen was 18% lower at the surface than in the core (37 versus 45 HRC). The former value is lower than the SAE recommended value (42–49 HRC) [9]. The quenched leaf also exhibited a disparate hardness at the surface and core (49 versus 63 HRC), but little difference between the two was found in the as-rolled condition (27 versus 28 HRC).

Based on the previous results, the hardness of the leaf surface was considerably reduced by the thermo-mechanical manufacturing process. This was mainly the result of steel decarburization, due to the lack of right control in the protective atmospheres of the heating equipments (forges and furnaces).

7. Static loading tests

Static loading tests were performed with a universal dynamometer. The spring was placed upside-down and gradually bent in the range from 0 to 107 mm, respectively, under a load 0 to 3810 kgf. Fig. 9 illustrates the linear relationship between the applied load and the extent of reversed bending, which is suggestive of an elastic behaviour. Flattening the spring required bending it by 97 mm with a 3560 kgf load. The maximum deformation (10 mm departing from the flattened position) was obtained with a load of 3810 kgf. After unloading, the spring regained its initial shape. Based on these results, the spring behaved elastically under static loads even as high as 3600 kgf – a value exceeding the design load (1940 kgf).

8. Fatigue tests

Fatigue tests were performed in accordance with SAE J1528 and the Venezuelan standard COVENIN 966-78. The tested specimen was placed upside-down in the machine and subjected to fluctuating loads from 970 to 3600 kgf at a frequency of 80 cpm. The test was finished as soon as cracks became apparent in the master leaf or in more than two bearing leafs.

The studied springs differed in their central hole, which was either cup-shaped (BAC specimens), of the form shown in Figs. 2 and 3, or flat (BAP specimens, Figs. 10 and 11).

The design of the BAC specimens, with recesses and ridges (cup-shaped holes), was intended to prevent mutual sliding of the leaves. Three specimens of this type, that were designated BAC1, BAC2 and BAC3, and two with a flat central hole (BAP1 and BAP2) were studied. Table 1 summarizes the results of the fatigue tests. The second column in the table states the first fractured leaf and, in brackets, the second in each specimen. As can be seen, the springs failed by effect of fracture in one of the first three leaves. This was unsurprising since such leaves must withstand the greatest working stresses as they are those deformed to the greatest extent when the spring is under bending loads [11]. Also, the leaves fractured at the hole – by exception, specimen BAC3 fractured tangentially to the hole edge. The hole is known to act as a stress raiser. The large differences in fatigue behaviour among specimens by effect of the hole geometry should be noted. Thus,

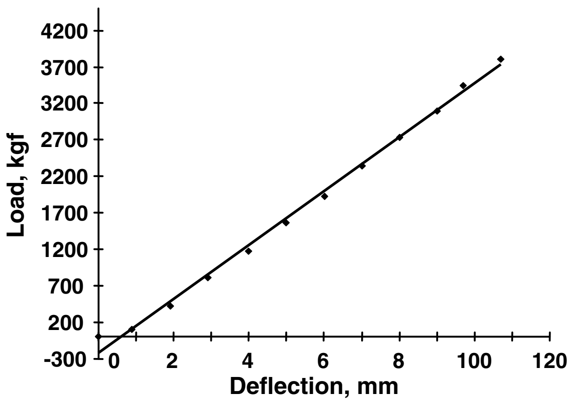

Fig. 9. Load versus deflection plot in the static loading test.

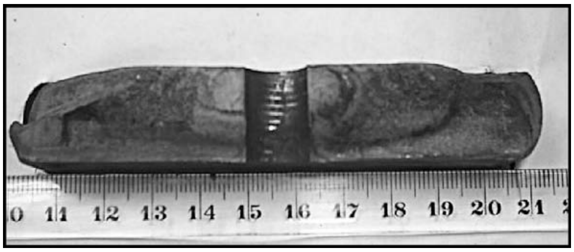

Fig. 10. Deformation marks caused by the threaded bolt in the hole of the master leaf in a spring subjected to the fatigue test.

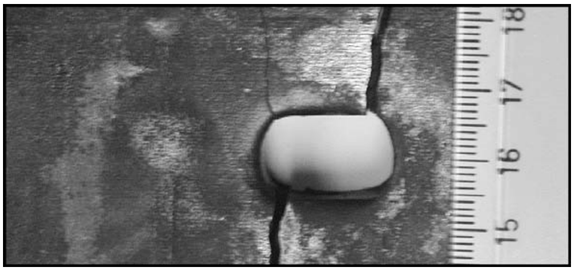

Fig. 11. Primary and secondary cracks in a leaf with a rectangular hole after fatigue testing.

Table 1
Fatigue life of leaf springs using two different central hole designs

Specimen	Fractured leaf (next)	Fracture site	Fatigue life (cycles)
BAC1	Third	Hole	17,147
BAC2	Second (third)	Hole (hole)	21,520
BAC3	First (second)	Hole tangent (hole)	23,118
BAP1	Second (third)	Hole (hole)	52,620
BAP2	First (second)	Hole (hole)	67,909

no spring with a cup-shaped hole, (i.e., no BAC specimen) reached 24,000 loading cycles; on the other hand, the flat-hole springs withstood more than twice that number (52,000 cycles). This can be ascribed to the increased stress concentration in the cup-shaped holes and its favouring earlier failure. Therefore, the cup-hole design is a poor design. Also worth noting is the fact that the springs with flat round holes performed relatively better despite the formation of ring-shaped marks normal to the hole axis (Fig. 10). Such marks were caused by the thread of the SAE 1020 steel bolt joining the leaves. The bolt is threaded by plastic deformation. The marks resulted from surface damage in the form of true notches in each leaf hole that reduce the fatigue strength of the steel; also, their presence in the hole inner walls indicates that the walls were not hard enough, probably by effect of decarburization.

The rectangular shape of the hole in the second leaf (Fig. 11), which was intended to facilitate fitting in assembling the springs, is also inadvisable as it favours stress concentration. As can be observed in this figure, the largest fatigue cracks were those starting at the corners of the rectangular holes. Such corners were quite sharp and acted as highly efficient stress concentrators that promoted fracturing. Fig. 11 also shows a secondary crack that started at the top left corner of the hole.

None of the springs subjected to the fatigue test reached the goal set by the standards: $>10^5$ cycles.

9. Conclusions

Premature failure in the studied leaf springs by fracture of a leaf was the result of mechanical fatigue caused by a combination of design, metallurgical and manufacturing deficiencies. Fatigue damage started in the vicinity of the leaf central hole by effect of the presence of stress concentrators and in the direction normal to the acting tensile stress. The stress concentrators included (a) the complex geometry of the hole, (b) its sharp corners, (c) fibering of the hole inner walls, (d) notches caused by the bolt thread and (e) various surface defects such as scabs and rolling lines in the starting sheets of an unclean steel. The negative effect of these factors was substantially enhanced by a defective heat treating of the leaves, including steel decarburization, during the manufacturing process, which led to inadequate hardness in the springs and, more important, the local presence of soft products (ferrite) in the material structure.

10. Preventive actions

One effective way of preventing fatigue failure is by minimizing stress concentrators resulting from design, metallurgical or manufacturing factors. The specific measures to be adopted for lengthening spring life begin with the selection of clean steel, free of surface defects. The leaf hole should be round and flat. Moreover, after heat treating the top corners of the major leaves should be trimmed into curved (rounded) form to further decrease the stress-raising action. This operation also eliminates partially the decarburized layer at the most critical hole region.

Decarburization of the leaves during the manufacturing process must be prevented. Likewise, heat treating should be conducted so as to obtain a pure tempered martensite structure. For a more detailed explanation, see Section 5.

Additional measurements of assistance with a view to increasing the fatigue strength of the springs include improving the surface quality of the leaves as regards both starting material (steel sheets) and manufacturing process (by avoiding fibering or the formation of inner notches in the hole). The use of a bolt threaded only at its ends might prove effective in this respect.

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