Residual stresses induced by shot-peening and fatigue durability of leaf springs

Conference Paper · August 2012

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Residual Stresses Induced by Shot-Peening and Fatigue Durability of Leaf Springs

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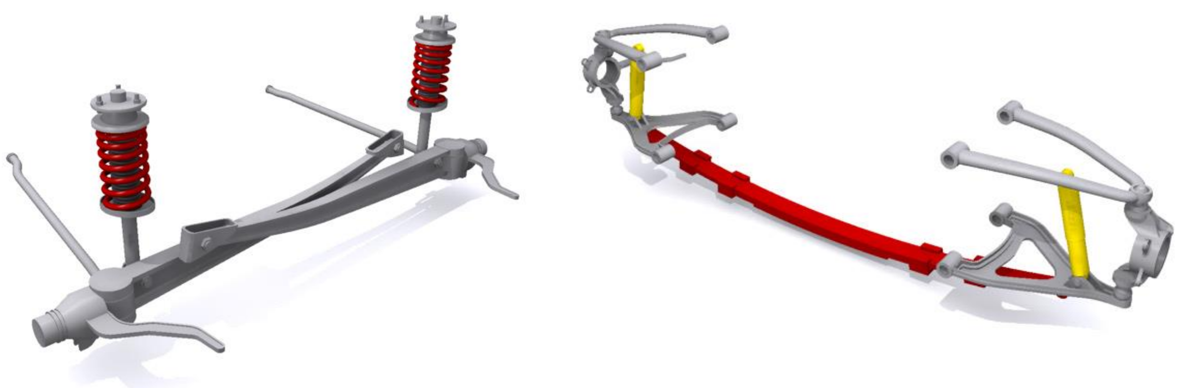
Keywords: shot-blast, shot-peening, automotive springs, x-ray diffraction, residual stresses, fatigue life

Abstract.
The improvement of fatigue life in parts subjected to cyclic stresses by application of mechanical surface treatment processes is already well known, both in the industry and in the academy. Dealing with automotive springs, the shot peening process becomes an essential step in manufacturing these parts. In the case of leaf springs, however, a systematic investigation of the effect of shot peening on fatigue life is still required. The aim of this work is to improve the knowledge of shot peening on leaf springs for vehicles, through the analysis of residual stresses by x-ray diffraction and fatigue tests on a series of samples that were subject to ten different peening schedules. Among the investigated processes, the usage of 1.0 mm diameter cast steel shot followed by a second peening with 0.3 mm diameter cast steel shot leads to better performance, regarding fatigue life. X-ray diffraction analysis shows that this improved performance is may be attributed to residual compressive stress maintained until a depth of 0.05 mm below the surface, which directly influences the fatigue crack nucleation. Residual stresses induced by shot-peening in larger depths, have no influence on sample fatigue life, showing that crack propagation is not affected by the induced residual stresses. Consequently, the durability of parts is improved by shot-peening exclusively due to this influence on crack nucleation at sample's surface. Correlations with the increased hardness and decreased ductility of the employed material are discussed.

Introduction

Suspension Systems

The automotive suspension system is responsible for the link between the structure of the vehicle and its wheels. Consequently, it is also responsible for the absorption of vibrations caused by irregularities in the road, improving vehicle maneuverability and user comfort. [1]
The main components of the suspension system are the springs (fig. 1), the bumpers, and the stabilizers (fig. 2). The stabilizers, by concept, are responsible to control the roll of vehicle during curves. The springs are the parts which support the vehicle weight, and absorb the majority of the energy generated by track irregularities while driving. They always work within the elastic zone under Hooke's Law (where strain is proportional to the stress), so this energy is fully absorbed by elastic deformation.
The bumpers are responsible to dissipate this energy absorbed by the springs, making it possible to drive the vehicle even on irregular tracks [1].



(A) (B)

Fig. 1 – (A) Coil Springs and (B) Leaf Springs. [1]

Fig. 2 – Stabilizer bar [1]

The springs for regular vehicles are found in many shapes (or configurations): coil springs, leaf springs, air springs, or torsion springs. Coil springs are more used on light vehicles. Leaf springs, heavier than coil springs, are more used on commercial vehicles (buses or trucks) [2].
In the present work we restrain our analysis only to leaf springs. Leaf springs are found in two configurations: semi-elliptic or parabolic (fig. 3). In both cases they are formed by steel leaves. In parabolic springs these leaves have variable thickness, based on a parabolic profile. In semi-elliptic springs they have the same thickness along its length. In both cases they are usually assembled as packages, but on parabolic leaf springs they can also be produced as mono-leaf springs.
Regarding fatigue life, the largest difference between parabolic and semi-elliptic springs is on stress distribution along its length. This distribution is basically constant in the parabolic case, which allows optimizing the project and reducing weight when comparing to a semi-elliptic working under the same work-load [2].

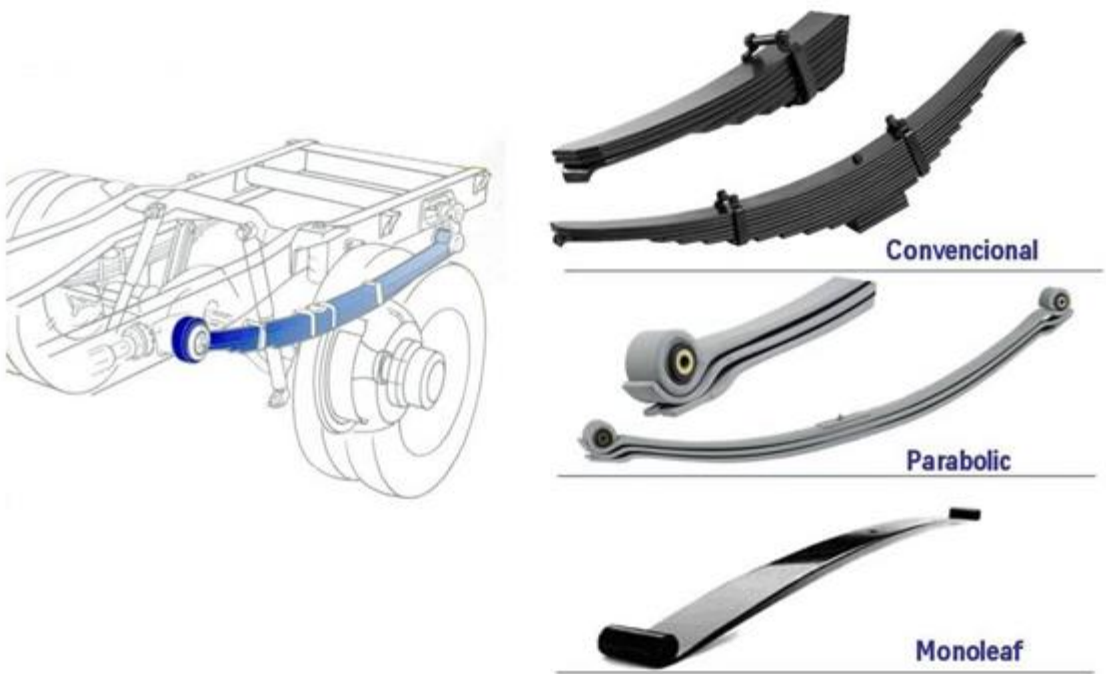


Fig. 3 – Different conceptions of leaf springs [2]

To grant these elastic properties to the springs, necessary due to the high loads to which these components are submitted during usage, the manufacturing process must guarantee a higher yield strength and tensile strength through quenching and tempering.
Besides that, a surface treatment must be done to maximize the fatigue properties. The most employed process for this objective is the shot-peening.

Manufacturing Process

We may divide the springs manufacturing process in four different steps: raw materials selection, mechanical working, heat treatment, and surface treatment.
Nowadays, for raw material, the spring industry is using mainly the SAE 6150, SAE 5160 and SAE 9254 steels for leaf spring manufacturing [3]. However, there are a lot of other options of spring

steels that can be used [4]. The microstructure of the material, when received from the steel mills, is basically pearlite+ferrite as obtained from rolling operation.
The first mechanical working process is the leaf end hot rolling. Depending on the spring project, this rolling process can produces either a parabolic profile on leaf's thickness, or only a uniform reduction on both end areas. This operation is typically performed around 1000º C.
After end rolling, the spring goes to the forging area. Spring eye conformation, holing, feature stamping, chamfer production, are some of the operations performed depending also on the spring project.
Next, the parts are send to the heat treatment operation (quenching and tempering). They are heated up around 1000º C, and rapid cooled on a oil tank at 80º C. The material, at this point, is very hard but also very fragile. So, the parts follow to the tempering stage, at around 400º C, to give its final mechanical properties.
After heat treatment, the springs are submitted to the shot-peening process. There are different peening techniques, all of them aiming at inserting compressive residual stresses on the surface of the material. This surface strain hardening, together with the compressive residual stresses, ideally maximizes the durability of the springs on fatigue condition. Schedule used in present work was done with cast steel shot media, but there are other alternatives using e.g. ceramic media, cut-wire media, sand, or other materials [5].
Then, the parts suffer a protective painting, and they are ready to deliver.

Material and Methods

The material used for this project was the SAE 9254, normally used on spring industry. The chemical composition of this production lot is according Table 1:

Table 1 – Chemical composition

%C	%Si	%Mn	%Cr	%P	%S	%Cu	%Ni	%Mo	%Al
0,52	1,25	0,64	0,64	0,013	0,005	0,04	0,18	0,03	0,014

Since the study is focused on shot-peening, all the material used on the present paper was produced together on rolling, taper, and heat-treatment. So micro-structure, mechanical properties, and process variations are minimized between the samples. All springs were produced with 500 HB hardness after tempering process.
In the present work 40 parabolic monoleaf springs were produced, divided on 4 different groups of 10 springs. Each group was submitted to different double shot-peening schedules, according Table 2:

Table 2 – Shot-Peening conditions

	Cast Shot Size First Peening (nominal)	Cast Shot Size Second Peening (nominal)
Condition 1	0,8mm diameter	-
Condition 2	0,8mm diameter	0,6mm diameter
Condition 3	0,8mm diameter	0,4mm diameter
Condition 4	0,8mm diameter	0,3mm diameter

All of these conditions were done under "stress peening", where the springs are peened under a stress condition, according Figure 4. Also, they were all peened with new cast shot media, on the same machine, under fixed process variables.

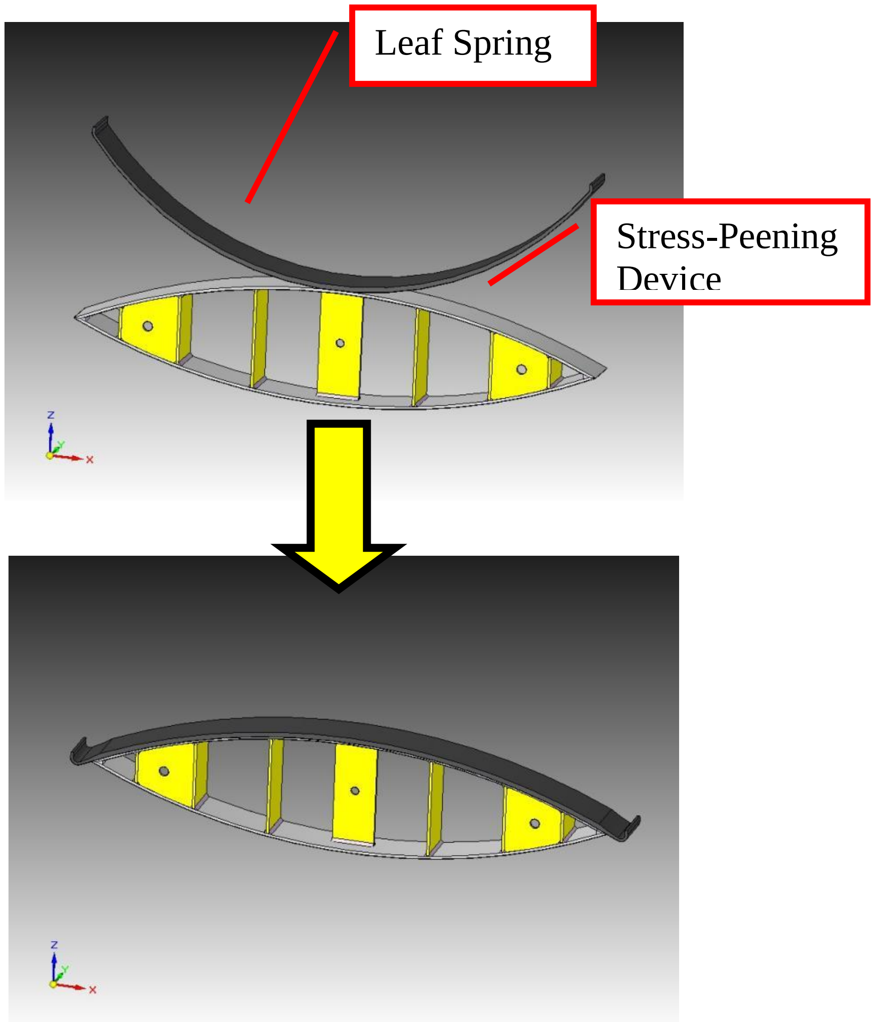


Fig. 4 – Setup for Stress-Peening Process

From these 10 springs sub-group, 7 of them were used for fatigue testing, and 3 of them were used for residual stress X-ray analysis. These quantities were chosen to minimize the standard deviation of the common fatigue results [6].
For the fatigue testing, a 1 Hz hydraulic machine was used. The conditions are on the Table 3:

Table 3 – Fatigue conditions

Minimum Load	35 Kgf
Nominal Load	500 Kgf
Maximum Load	645 Kgf

For X-ray residual stress measurement, a Rigaku DMAX 2000 was used, with Cr tube, 40 kV and 20 mA as reference. The equipment is from x-ray diffraction lab from IPEN/CNEN-SP, Brazil. The samples were extracted from the springs on identical positions, and a residual stress profile was measured over 9 different depths (0,00mm / 0,02mm / 0,04mm / 0,06mm / 0,10mm / 0,15mm / 0,20mm / 0,25mm / 0,30mm). The material removal was performed by chemical etching.

Results

The fatigue life results are on the Figure 5. They are represented as the median of the corresponding Weibull distribution, B50, that is, the number of reversals for which 50% of the samples will survive [7]. The Figure 5 also shows the 90% confidence intervals, to represent the dispersion of the fatigue life on each condition.

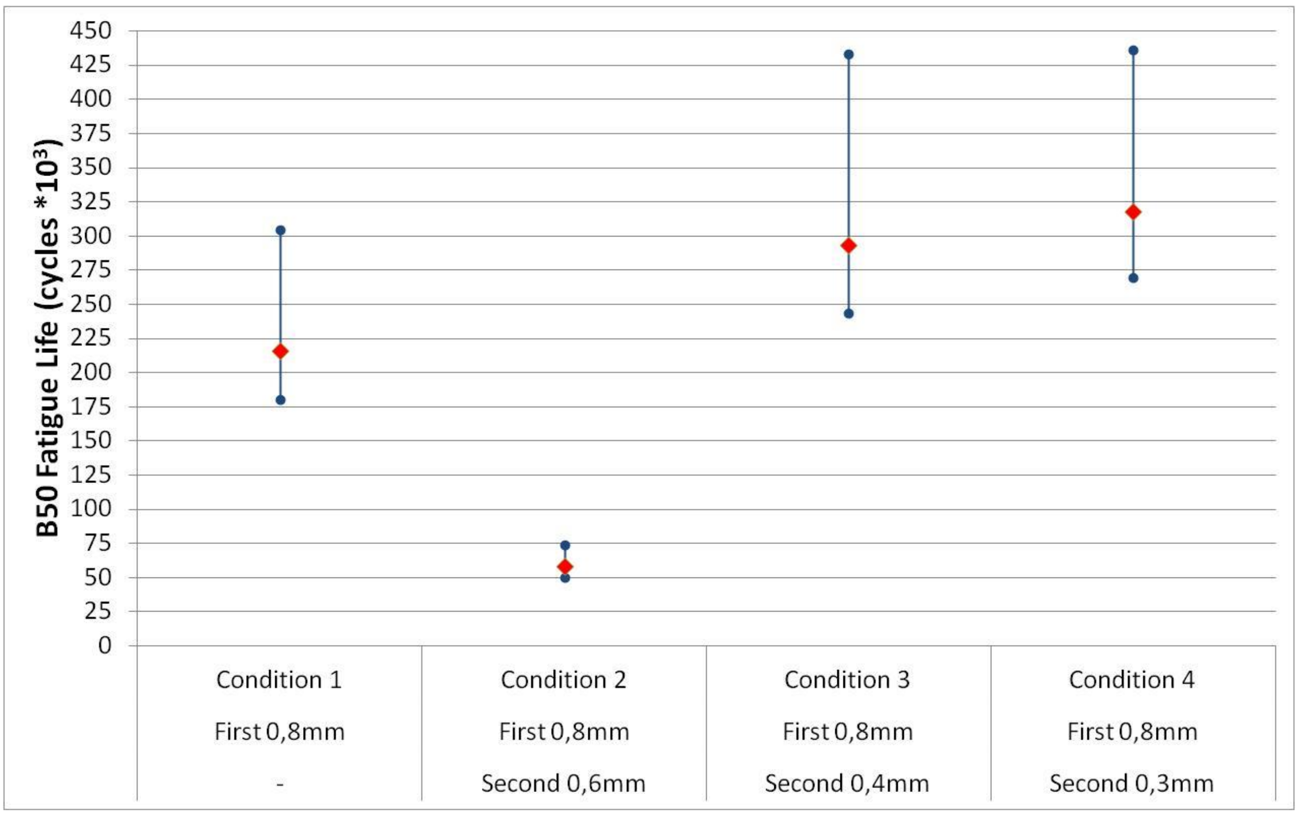


Fig. 5 – B50 fatigue life results

The measured residual stress profiles are on Figure 6. The results are a simple average from 3 samples measurements. Since the standard deviation from these 3 samples was always between 50MPa, we can assure that the results are statistically representative.

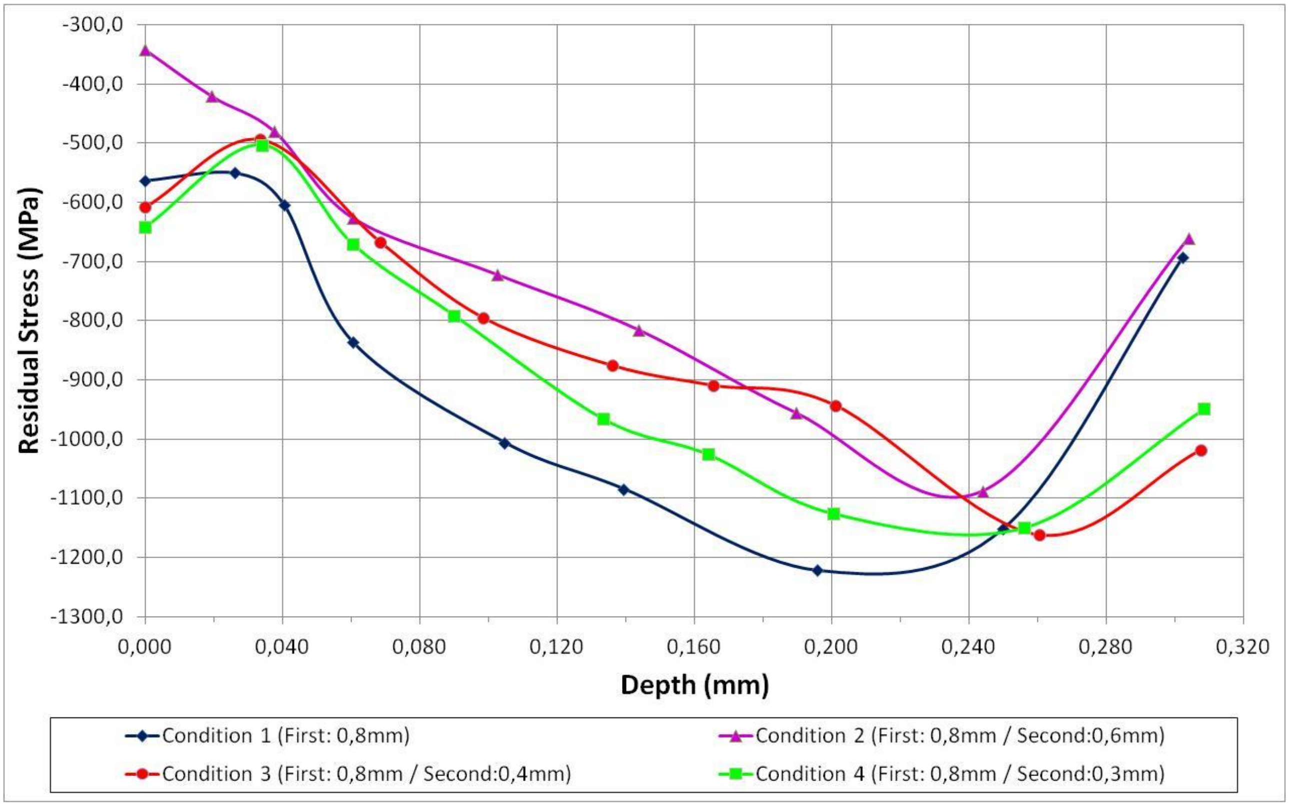


Fig. 6 – Residual Stress Profiles

The fatigue life results demonstrate that the double shot-peening is effective when the second peening is done with smaller shot media (maximum 0,4mm diameter). The B50 life results are at least 50% larger than the single peening samples when using 0,4mm and 0,3mm spheres. However, the fatigue life is significantly reduced when we use a 0,6mm diameter media on the second peening.

We can explain this result analyzing the fig. 6 results. On all double-peening samples some stress-relief phenomena occurred. This, at principle, would result on smaller durability. But on Condition 3 and Condition 4,until 0,02mm depth, we experienced a small (but clear) increase on the compressive residual stresses (45 MPa on Condition 3 and 80 MPa on Condition 4).

Conclusion

- For springs, the double-peening technique is consistent as an improvement on fatigue life when using smaller second-peening media (0,4mm and 0,3mm diameters);
- When working with high stress amplitudes components such as springs, produced with low tempering temperatures for higher hardness, the crack nucleation mechanism controls the durability. This is supported by the residual stress results, which shows that the fatigue life is strongly affected only by surface compressive residual stresses (up to 0,02mm depth).
- Even with a stress relief mechanism working sub-superficially, the fatigue lives suffered no negative impact. So the crack propagation mechanisms, for these components, are much less important comparing to the crack nucleation mechanisms.

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