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Technical Report

Role of residual stresses induced by double peening on fatigue durability of automotive leaf springs

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ABSTRACT

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. 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 the present work is to improve the knowledge on the role of shot peening in manufacturing 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 0.8 mm diameter cast steel shot followed by a second peening with 0.3 mm diameter cast steel shot leads to optimal performance, regarding fatigue life. X-ray diffraction analysis shows that this improved performance may be attributed to residual compressive stress maintained until a depth of 0.02 mm below the surface, which directly influences fatigue crack nucleation. Residual stresses induced by shot peening in larger depths have no influence on the sample's fatigue life.

1. Introduction

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 [1–3].

The main components of the suspension system are the springs, the bumpers, and the stabilizers. The stabilizers, by concept, are responsible for controlling the vehicle's path during curves [1]. The springs are the parts which support the vehicle weight, and help in absorbing the major part of the energy generated by track irregularities while driving [2]. They work primarily within the elastic zone under Hooke's Law regimen (where displacement is proportional to the force), so this energy is primarily stored by elastic deformation.[1] The bumpers dissipate this energy, making it possible to drive the vehicle even in irregular tracks [3].

Springs for regular vehicles are found in different shapes (or configurations): coil springs, leaf springs, air springs, or torsion springs. Coil springs are preferentially used on light vehicles, while leaf springs, heavier than coil springs, are more common on commercial vehicles (buses or trucks) [1]. The preference for leaf springs in heavy vehicle suspensions, however, is not only economical or project related. Numerical simulations of soil vibration caused by vehicle motion demonstrate that leaf spring suspensions produce lower levels of ground vibration in traffic, so this preference could also be regarded as "environmental" [4,5].

In the present work we restrain our analysis to leaf springs. Leaf springs are found in two configurations: semi-elliptic or parabolic [6]. 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 for project optimization and weight reduction compared with semi-elliptic springs working under the same work-load.

To grant these elastic properties to the springs, necessary due to the high loads to which theses components are submitted during service, the manufacturing process must guarantee high yield strength and tensile strength through quenching and tempering. Besides that, a surface treatment must be performed to maximize the fatigue properties. The primary process in this case is shot-peening [6].

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[1] Part of the energy may also be dissipated in the springs by friction between the part and its supports in the structure.

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1.1. Manufacturing process

The spring manufacturing process may be divided into four steps: raw material selection, mechanical forming, heat treatment, and surface treatment. Presently the spring industry uses mainly the SAE 6150, SAE 5160 and SAE 9254 steels for leaf springs [7]. Other material's options are, however, available [8]. The material's micro-structure, as received from the steel mills, is basically pearlite + ferrite as result of the previous hot rolling operation.

The first mechanical forming process is an additional hot rolling process applied to the leaf, called "end rolling". Depending on the spring project, this rolling process produces either a parabolic profile on leafs thickness, or a uniform reduction on both end areas. This operation is typically performed around 1000 °C.

After end rolling, the spring is lead 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 to around 1000 °C, and oil quenched in a tank maintained at around 80 °C. The parts follow to the tempering stage, at around 400 °C, to grant their final mechanical properties. After quenching and tempering the micro-structure is fully martensitic, except for a thin ($\lesssim$10 μm) ferritic layer close to the surface, which originates from decarburization.

After heat treatment, the springs are submitted to the shot peening process. There are different peening techniques, all of them aiming at producing 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 loading. The shot peening 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 [9,10]. Finally, the parts are subject to a corrosion protective painting, and they are ready to deliver.

1.2. Shot peening, residual stresses and fatigue durability

The role of shot peening in producing compressive residual stresses at the part's surface, thus enhancing its fatigue performance, is already recognized for several decades [11]. Detailed investigations on the effect of shot peening process parameters on fatigue durability are, however, not so common. Tekeli [12] investigated, using standard test specimens loaded in a rotating beam fatigue machine, the influence of shot peening intensity (measured in Almen) on fatigue durability of SAE9245 steel, showing that an optimum intensity exists. A too severe intensity (over-peening) causes deterioration of fatigue strength, which was attributed by the author to surface damage (cratering, micro-cracking). More recently, Olmi et al. [13] investigated the effect of different surface finishing schedules (including double shot peening) over the fatigue performance (measured by the part's fatigue limit) of case hardened gears. These authors conclude that double shot peening has no effect on enhancing the part's fatigue limit, but that it does affect data dispersion, decreasing it (hence, increasing results reproducibility). Due to the lack of information, great deal of interest has been given to the development of predictive analytical models, capable of estimating the subsurface residual stress profile produced by different shot peening schedules [14–17]. These models can be, eventually, employed for fatigue life prediction [16–19].

The recognized importance of shot peening on extending fatigue lives of specific components (e.g. of the steel leaves used in leaf springs) means that the industrial praxis already has considerable knowledge on the effect of applying different shot peening schedules on this property. This knowledge, however, most probably, was acquired in an empirical way. The aim of the present work therefore, is to extend this knowledge basis, by characterizing the different residual stress profiles produced by different schedules and correlate them with the part's fatigue durability, in an attempt to understand the relevant aspects, which could be used for process optimization in the present application.

2. Material and methods

The material investigated in the present work is the SAE 9254 steel, conventionally employed in the spring industry. The analyzed chemical composition, as determined by the supplier, using optical emission spectrometry in samples taken from the melt in the tundish, prior to continuous casting, is given in Table 1:.

Since the study is focused on shot-peening, all parts used on the present paper were produced simultaneously in the rolling, taper, and heat-treatment steps. So micro-structure, mechanical properties, and process variations are minimized between the samples. All springs were produced targeting 500 HBW Brinell hardness after tempering process.

The leaves were submitted to painting at room temperature prior to testing, for corrosion protection. All leaves presented a thin decarburized layer at the surface. No attempt was made to eliminate this layer, since it is also present in the produced part. The thickness of this layer was analyzed and found to be compatible with the historical average of the leaves, as received by the factory. Hence the employed leaves are representative samples of the produced parts.

For the present work 40 parabolic mono-leaf springs were produced, divided into 4 different groups of 10 springs each. All leaves had varying thicknesses, consistent with the parabolic profile. Leaf thickness correspond to 8.7 mm at the center and 4.5 mm at the borders. The profile was produced by hot rolling. Each group was submitted to different double shot-peening schedules, according Table 2:.

Since the leaf operate permanently under bending load, only the tractive side of the leaf was submitted to shot peening. The leaves are arched during the quenching procedure. Shot peening slightly changes the arching radius, but this effect is already approximately predicted in the component's design. Small corrections are applied after tempering and shot peening, to reach the part's final dimensions.

All of these conditions were done under stress peening condition, in which the springs are peened under a strained configuration, such that they are bent in the opposite direction of their equilibrium shape (i.e. the shape corresponding to zero load).

Shot peening of all samples was conducted in the same machine, equipped with stationary turbines, that is, the samples are moved while submitted to the procedure. Machine "hot spot" was determined to be identical for all conditions. A single pass

Table 1
Analyzed composition of the steel batch used for production of the investigated steel leaves (compositions are given in mass fraction, the last significative digit is an estimate of the resolution of the analytical method).

wt.% C	0.52
wt.% Si	1.25
wt.% Mn	0.64
wt.% Cr	0.64
wt.% P	0.013
wt.% S	0.005
wt.% Cu	0.04
wt.% Ni	0.18
wt.% Mo	0.03
wt.% Al	0.014

Table 2
Summary of shot peening conditions (CS = cast shot size).

	CS1 (nominal)	CS2 (nominal)
Condition 1	0.8 mm ∅	None
Condition 2	0.8 mm ∅	0.6 mm ∅
Condition 3	0.8 mm ∅	0.4 mm ∅
Condition 4	0.8 mm ∅	0.3 mm ∅

was used for all samples, machine operating current, turbine rotation speed and shot media level in the reservoir were kept constant in all cases, to warrant that all process conditions are the same, apart from the diameter of the shot media. Shot-peening coverage was determined using an image analyzer and was measured to be over 100% in all cases, and this value was attained already in the first peening. The precise coverage was not measured, but since all shot peening conditions are constant, it is assumed that sample coverage is also constant. The used shot media is predominantly spherical, as typical for cast media. Granulometric distribution of the shot media complies with ASTM: E11-09e1 standard, under specification SAE S330 (0.8 mm), SAE S280 (0.6 mm), SAE S230 (0.4 mm) and SAE S170 (0.3 mm). New shot media was used in all samples.

Saturation condition was not calculated, since the equipment used in the experiments is setup for production work, with the shot peening cycle time fixed based on a 100% coverage minimum. The shot-peening treatment time was fixed for the first and the second peening, in all conditions. The main goal was to fix all shot peening parameters, so that even if saturation cannot be guaranteed, at least all samples are processed in the same way as the produced parts.

From the 10 springs sub-groups, 7 were reserved for fatigue testing, and 3 were used for residual stress X-ray analysis. These quantities were chosen to minimize the standard deviation of the common fatigue results [20]. Fatigue testing was conducted at constant amplitude, under displacement control, at 1 Hz, using a hydraulic machine. Since the springs operate entirely in the elastic regimen during testing, the relation between load and displacement is biunique. The load conditions are given on Table 3:.

These loading conditions are schematically represented in Fig. 1. These conditions are prescribed by a vehicle manufacturer as a quality control criterion. In this sense, the nominal load corresponds to the strained condition characteristic of the vehicle at rest. A Finite-element simulation was used to estimate the stress state in the external fiber of the leaf (that is, the maximum nominal stress at the leaf surface), which correspond to 114 MPa at the minimum load and 1296 MPa at maximum load.

A Rigaku DMAX 2000 diffractometer was used for the X-ray residual stress measurements, operating with Cr tube, under 40 kV and 20 mA as reference. The samples were extracted from the springs on identical relative positions, and a residual stress profile was measured over 9 different depths (0.00 mm/0.02 mm/0.04 mm/0.06 mm/0.10 mm/0.15 mm/0.20 mm/0.25 mm/0.30 mm). No surface preparations was applied prior to residual stress measurement. The material's removal was performed, only in the shot peened side and only in the analyzed region, by chemical etching using a H_2O + 50% HCl solution. The targeted depths were evaluated using the etching time and checked using a standard micrometer with 1 μm resolution. The ambient temperature during measurements was kept constant within the 25 ± 1 °C range. Residual stresses were determined using the $\sin^2(\psi)$ method.

Table 3
Load settings used for the fatigue testing.

Minimum load	343 kN (35 Kgf)
Nominal load	4900 kN (500 Kgf)
Maximum load	6320 kN (645 Kgf)

Surface roughness of all samples was measured using a Mitutoyo SJ400 rugosimeter. Measurements were performed at two different regions of the produced part and the results are presented as arithmetic averages of all samples belonging to a group.

3. Results

The fatigue life results are on Fig. 2. They are represented as the median of the corresponding Weibull distribution, B50, that is, the number of reversals for which 50% of the samples survive [21]. Fig. 2 also shows the 90% confidence intervals of the results, to represent the dispersion of the fatigue life on each condition.

The measured residual stress profiles are shown in Fig. 3. The results are represented by the average from 3 samples measurements. Since the standard deviation from these 3 samples was always of the order of 50 MPa or less, we can assure that the results are statistically representative and that the different shot-peening conditions produce different residual stress profiles.

The fatigue life results demonstrate that the double shot-peening process is not effective when the second peening is performed using the largest shot media (0.6 mm diameter), that is, compared with condition 1 (single shot peening), fatigue life is significantly reduced in this case. On the other hand, B50 life results are at least 50% larger than the single peening samples when 0.4 mm and 0.3 mm spheres are used.

We justify these results by analysis of Fig. 3. Considering only the residual stress profile, the only point which correlated with the observed B50 values is in the surface. To stress this point, Table 4 shows the residual stress values (and corresponding standard deviation) for the 0.0 mm depth. Obviously the large spread in the fatigue life data does not allow to draw a conclusion about the effect of shot peening on fatigue durability for conditions 3 and 4, but at least the trend in B50 is consistent with the residual stress values at the surface. The anomalously small standard deviation for condition 3 is probably a consequence of the statistical fluctuation of the measurements, after all, the variance (and hence, the standard deviation) of a statistical sample is, itself, a stochastic variable.

Comparing the curves for conditions 1 and 2, we observe that the expressive reduction in fatigue life of the later can be justified by a large reduction (of about 200 MPa) in the compressive stress profile up to 0.2 mm depth. This stress-relief, compared with the single peening case, is also observed in the other double-peening samples, but in a lesser degree (and not at the surface). This, in principle, would suggest a smaller durability in all cases, if fatigue crack propagation were the controlling aspect of the failure. Conditions 3 and 4, however, present improved fatigue strengths compared with conditions 1 and 2. These leaves experience a small (but evident) increase in the compressive residual stresses (−60 MPa on Condition 3 and −150 MPa on Condition 4, around 0.14 mm depth), compared with condition 2. Furthermore, the residual stress level increases at the surface (0.0 mm depth) and remain larger at larger depths.

The origin of this stress relief observed for the double peening samples is unclear. Three hypotheses were raised to explain this phenomenon. First, the residual stress profiles produced by shot peening contain a deep tensile stress zone, which is needed to equilibrate the compressive stresses produced at the surface (see, for example, [22]). According to this picture, the observed reduction in the stress levels would result from the superposition of the stress field produced by the first peening and the tensile stresses of the second peening, which, being less intense, produced a

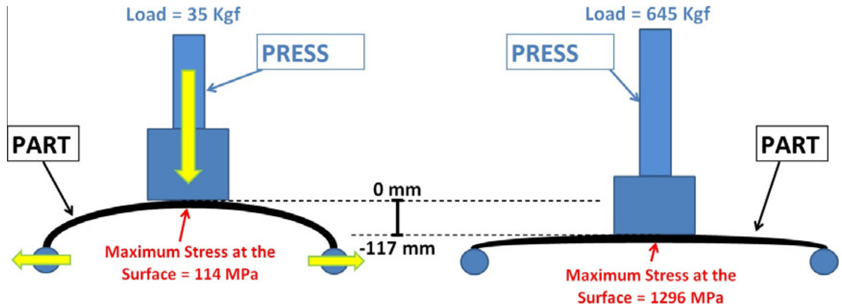

Fig. 1. Schematic representation of the loading conditions used for fatigue testing.

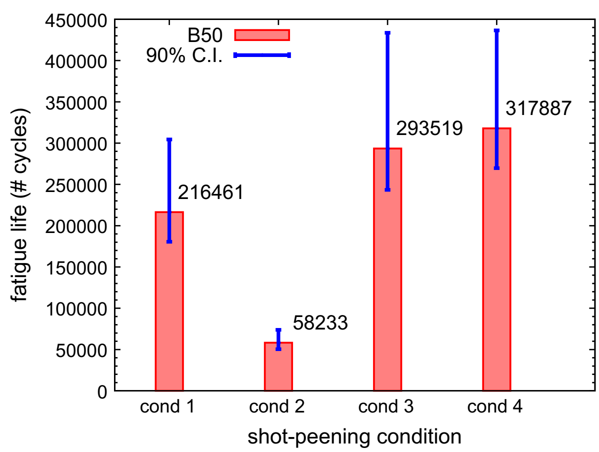

Fig. 2. Values of B50 obtained for the Weibull plots of the results in the four conditions investigated in the present work. The bars represent the limits of the 90% confidence interval (C.I.) for the data.

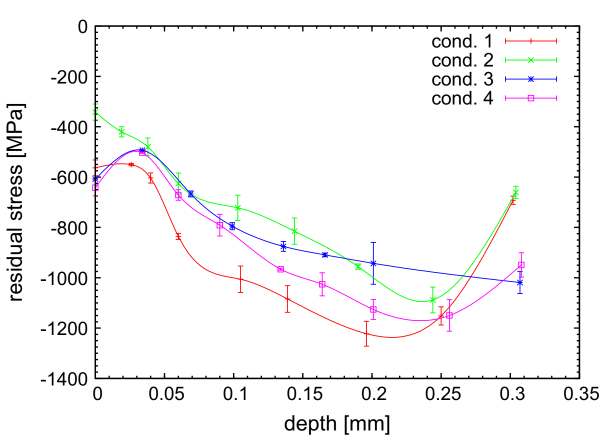

Fig. 3. Residual stress profiles resulting from the different shot-peening schedules investigated in the present work.

Table 4
Residual stress values at 0.0 mm depth for the different shot peening conditions.

Condition	σ_{res} (MPa)	St. dev. (MPa)
1	−563	31
2	−342	32
3	−608	1.4
4	−642	33

shallower residual stress profile. This contribution must be present, but it is unclear if it can account for the large reduction in compressive stress observed in the profiles and, of course, it is incompatible with the uniform reduction observed in Condition 2.

A second possible source for this stress relief would be the localized heating produced by the intense plastic deformation at the surface layer. The heat input produced by the individual shot impacts may produce a steady state temperature field in the sample, reaching conditions for onset of recovery mechanisms in the plastic-deformed zone. This would relieve the stress levels. Again, this effect must be present in the sample, and it is surely compatible with the more-or-less uniform residual stress reduction in Condition 2, but it is unlikely that it can account for all of the observed stress relief (and, of course, the intensity of compressive stress at the surface layer increases for Conditions 3 and 4, which is not compatible with this picture).

A third possibility would be attributing this effect to some plasticity-related effect. It is well known that the residual stress profiles produced by shot peening relax under cyclic loading [16,18,23]. The results shown by Zhuang and Halford [23], in particular, show that a large reduction in residual stress levels are possible after a few cycles of fatigue loading. A double shot peening schedule, that is, the application of a approximately constant load, then a stress release, followed by a second period of constant load, could be regarded as similar a single cycle of a fatigue loading with null stress ratio ($R = 0$).

Apart form the already mentioned increase of residual stress at the surface, there are, other factors related to the double shot-peening process which controls fatigue life [19]. Most probably differences in surface quality are also responsible for the observed durability changes. It can be argued, for example, that small cast shot size could have an effect similar to conventional grinding, leveling the roughness induced by the first shot-peening schedule.

Table 5 shows the results for the profile parameters for the different conditions, including the average roughness, R_a, the average distance between peak and valley in a sampling length, R_z (according to DIN 4775), and the maximum height of the profile, R_t.

As observed, these measurement do not correlate with the observed B50 lives. In particular, comparing conditions 1 and 2, we observed that roughness is considerably reduced in the later, but this is also the condition which produces the shortest durability.

In any case, the results clearly suggests that the sample surface state (up to a 0.02 mm depth) controls the fatigue durability in these parts. This seems to indicate that crack nucleation (or, at least, crack growth initiation) is the dominant aspect. A direct fractographic observation was not possible, since some of the samples do not present clear discernible propagation regions. This would point out, indeed to a very short propagation phase in these cases. In fact, crack propagation, even in the microcrack region, should be more difficult in the case of Condition 1, based only on the residual stress profiles. This has a deep implication for the industrial praxis: if only the surface residual stress levels are relevant for under-

Table 5
Roughness profile parameters for the four investigated conditions. Values in μm.

Condition	R_z	R_a	R_t
1	41.3 ± 2.3	7.07 ± 0.49	52.5 ± 3.1
2	37.5 ± 4.1	5.24 ± 0.42	41.7 ± 2.5
3	37.1 ± 7.0	6.71 ± 0.75	46.9 ± 5.6
4	33.2 ± 2.1	5.52 ± 0.31	41.1 ± 3.7

standing fatigue durability, the determination of the full residual stress profile is not necessary for comparing the effect of different shot peening schedules in these parts, simplifying the procedure.

Direct comparison of the present results with those reported in the literature is difficult, since the results are deeply affected by process variables. As an example, [6] report residual stress profiles with minimum peaks around −600 MPa for a single peening condition in SAE 5160 steel, peened with S330 shots. Compared to the present results for condition 1 (Fig. 3), the maximum compressive residual stress in the present experiments is about 100% larger. It is interesting to note that both cases were analyzed in the same instrument, using equivalent experimental procedures, so the differences should be attributed to variations in the shot peening procedure and, of course, to the different steel. In the same line, [18], report residual stress profiles for single peening which approach the present values for the largest peening intensity, but in this case the profile is shallower, even using 1.0 mm shots.

Results in fatigue life are even more difficult to compare, since loading, shape and configuration of the present springs are different. Even so, the results obtained in other works are consistent with our conclusion. For example, [18] obtains an increased fatigue life with increasing shot peening intensity. This results correlates with a homogeneous increase in residual stress with increasing shot peening intensity. In particular [12] also attributes the increase in fatigue life to compressive stresses developed in the surface layer of the samples.

4. Conclusions

The double-peening technique is consistent as an improvement on fatigue life of leaf springs when using smaller second-peening media (0.4 mm and 0.3 mm diameters). These components operate at high stress amplitudes and are processed at low tempering temperatures for higher hardness. In these cases crack nucleation controls the durability. This is supported by the residual stress profile results, which shows that the fatigue life is strongly affected only by surface compressive residual stresses (up to 0.02 mm depth). Even with a stress relief mechanism working sub-superficially, the fatigue life suffered no negative impact. So the crack propagation, for these components, is considerably less important compared to crack nucleation, as supported by the lack of discernible propagation features in the fracture surfaces of some of the samples.

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