The effects of shot peening highly loaded compression springs

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Keywords: Fatigue, Residual Stress, Shot Peening, Compression Spring, X-Ray Diffraction, Dual Peening

Introduction

For severe duty spring applications the designer has to achieve additional gains once the material and geometry have been selected, particularly if the application has weight and space restraints. The compression spring in this test study is typical of one used in a demanding off-road vehicle suspension. The cyclic loads applied during fatigue tests were high enough to cause failure in approximately 11,000 cycles without shot peening.

For most fatigue applications, this would be considered low cycle (high stress) and not well suited for shot peening which is usually applied in high cycle (low stress) loading. This study will demonstrate that various peening treatments produced excellent fatigue life improvement.

Objectives

The objectives of this study were the following:

1. Design a compression spring similar to those used in the off-road recreational industry.
2. Design & manufacture a fatigue test stand that could withstand high loads for months of testing
3. Generate a matrix of shot peening treatments to produce different amounts of residual compressive stress
4. Measure the shot peening residual compressive stress via X-Ray Diffraction (XRD)
5. Correlate the residual stress to fatigue life performance
6. Evaluate the effects of a post shot peening bake cycle on fatigue performance.

Methodology

The dimensions and material properties of the compression spring used in this study were as follows: Free Length = 391.2 mm, Outer Diameter = 111.8 mm, Wire Diameter = 12.7 mm, Tensile Strength = 1931 MPa (min).

In order to simulate the severe test conditions of similar real world applications, the applied stress for fatigue testing was 61.5% of material tensile strength. This applied stress would cause mechanical yielding on the first test cycle, establish a new free length and change overall properties of the spring.

In order for the spring to not take a set during testing, the spring was (initially) designed with a longer free length of 431.8 mm then cold set (compressed) to solid height. This process induces mechanical yielding and establishes the desired free length (391.2 mm). All spring iterations were cold set (to solid height) so that comparisons would be equal.

The following shot peening iterations had residual stress levels measured using XRD and were subsequently fatigue tested. All iterations had a standard post peen 204˚C baking cycle.

- No peening (baseline)
- 230R @ 0.30-0.40 mm A (regular hardness shot)
- 230H @ 0.30-0.40 mm A (fully hardened shot)
- 460H @ 0.20-0.25 mm C (fully hardened shot)
    - With & Without post peen 204˚C bake)
- 460H-230H dual peen (0.20-0.25 mm C followed by 0.25-0.35 mm A)
- Reversing the order of shot peening & cold pressing

Results and analysis

Figure 1 shows the results of XRD measurements for the majority of the shot peening iterations described in the previous Methodology section. Figure 2 shows a summary of fatigue testing for all peening iterations

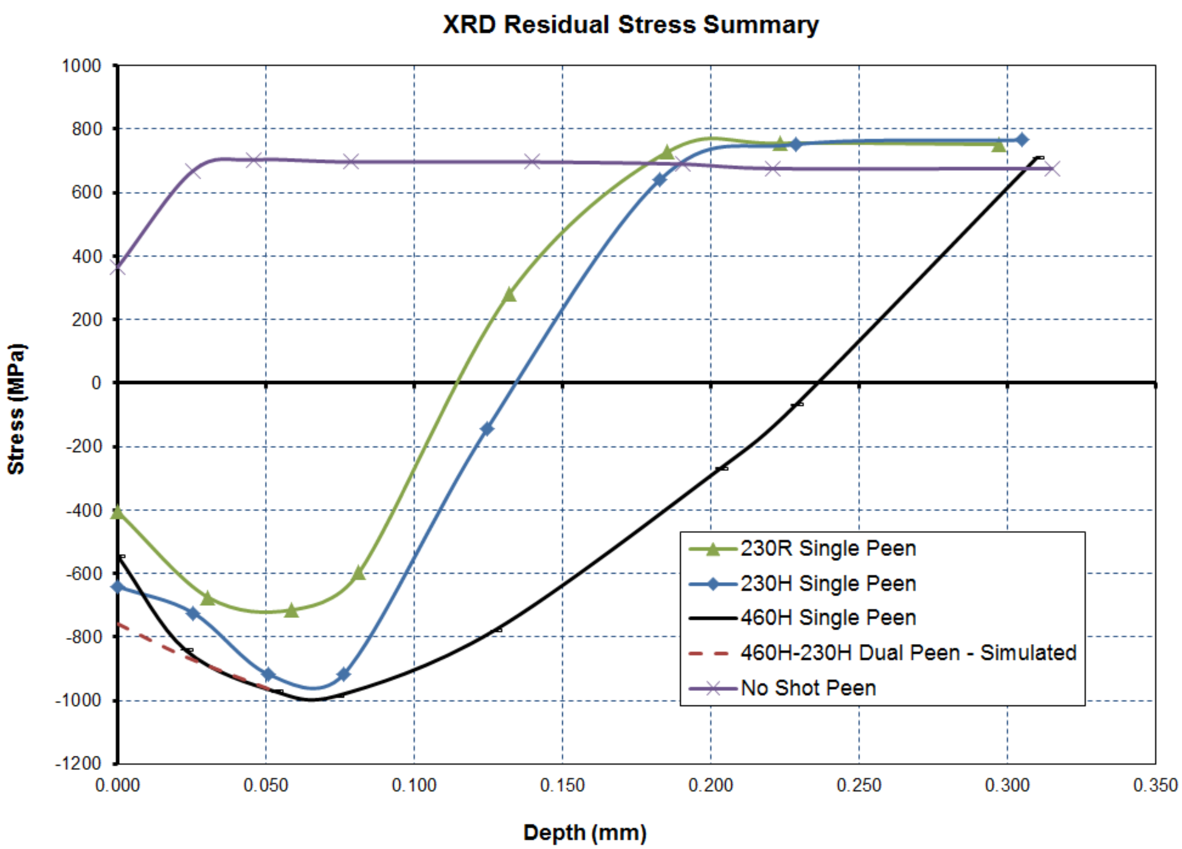

Figure 1: Summary of Residual Stress Results

As a compression spring goes normal operation the axial stroke of the spring produces torsional loading/stress on the spring wire. Torsional stress is in a tensile direction with the highest stress at the surface. As shown in Figure 2, the unpeened springs failed at approximately 11,000 cycles. This is typically considered low cycle (high stress) fatigue where shot peening may not produce notable improvements.

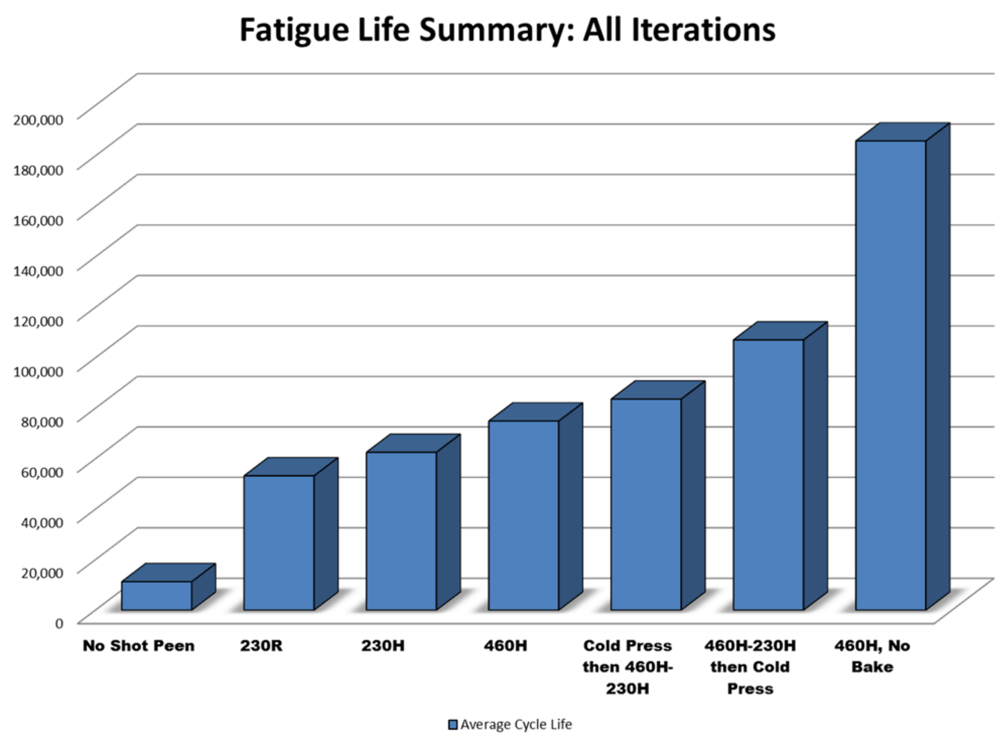

Figure 2: Summary of All Fatigue Testing

For this spring application, it is important to note the absolute difference in residual stress with & without shot peening. Without shot peening, the inner diameter (ID) of the spring exhibits a high magnitude of residual tensile stress (~ 700 MPa) in the near surface region from the coiling process to manufacture the spring. The various shot peening treatments produce residual stress in the opposite, compressive stress direction. 230R shot produced slightly more than 700 MPa of compressive stress while the 230H and 460H shot produced about 950-970 MPa of compressive stress slightly below the surface.

Under load the Total Stress (TS) a spring experiences is the summation of residual & applied stress. Before shot peening, the ID is in a residual tensile condition which will accelerate a fatigue failure as applied (torsional) stress is also in the same tensile direction. All shot peening iterations produced high magnitudes of compressive stress that are in the opposite direction as the applied tensile stress during fatigue loading. The TS equation described previously would indicate the shot peened spring experiences a much lower (total) stress as the applied stress is reduced by the amount of residual compressive stress from shot peening.

When comparing the different shot peening iterations, it is clear that a higher magnitude of residual compressive stress produced better fatigue life. When comparing the similar sized 230R & 230H shot, the harder 230H generated both more magnitude & depth of compressive stress. This is because the 230H is harder than the spring and the 230R shot is softer than the spring. This resulted in 53,200 life cycles for the 230R and 62,500 cycles for the 230H.
When comparing the 230H & 460H shot iterations, the larger 460H shot had a deeper compressive layer with similar compressive stress in the near-surface region. This resulted in 62,500 life cycles for the 230H and 74,900 cycles for the 460H.

Since fatigue cracks usually start at the component's surface, increasing the compressive stress at the surface is important. When comparing the (single peen) 460H to the dual peen 460H-230H, the compressive stress is essentially the same throughout the depth except for an increase of surface compressive stress from the second (230H) peening operation. Even though the compressive stress increase is only experienced in very near-surface region, the fatigue life improved almost 50% (74,900 cycles for 460H single peen & 107,000 cycles for the 460H-230H dual peen).

This data demonstrates that for surface induced fatigue failures, higher surface stress produces better fatigue performance than deeper compressive depth. The majority of notch sensitive fatigue applications in existence have surface initiated fatigue cracks.

Order of Shot Peening & Cold Pressing

Figure 2 shows that reversing the order of the dual peen & cold pressing was reviewed. This was done as an experimental curiosity. As Figure 2 demonstrates, performing the cold press after the dual peen produced better fatigue results (107,000 versus 83,600). From a spring manufacturing perspective, it is desirable to the cold press as the second operation. This allows the spring manufacturing to hold a tighter tolerance than if the shot peening was performed second.

Post Shot Peening Bake

The majority of shot peened springs are used in high cycle (low stress) fatigue applications. These springs would typically achieve 50,000 (or significantly more) cycles without shot peening. Shot peening is well suited for these springs. There are a number of spring studies validating the process of performing a low temperature bake (~ 204˚C) bake after peening to further enhance the fatigue improvement from shot peening.

This study produced a very interesting result when a single 460H (single) shot peen without post peening bake produced by far the best fatigue life of the study. As a matter of fact, the single peen – no post bake produced almost twice the fatigue life of the dual peen with post peening bake.

The important takeaway from this study is to not perform a post peening bake on very high stress (low cycle) spring applications. The authors did not have the time or resources to determine what stress level (or life cycles) when a designer would know to avoid the post peen bake. However, the authors are confident in stating that most springs that are in fatigue environments are higher cycle (lower stress) fatigue and should have a post peening bake process.

Conclusions

Dramatic improvements in low cycle (high stress) fatigue applications are achievable. This is dependent upon the residual stress condition prior to shot peening. The compression spring in this study exhibited a high magnitude of residual tensile stress from manufacturing. Shot peening converted to surface of the spring from high residual tensile to a high residual compressive stress.

Usage of harder shot produced greater magnitude of residual compressive stress. The more compressive stress that was produced from various shot peening iterations, the better the overall fatigue improvement. Harder shot & dual peening had a more beneficial effect on residual stress and fatigue life than higher shot peening intensity.

Most spring shot peening applications benefit from a low temperature baking operation after shot peening. However, very highly stressed springs perform better without a post peening baking operation.