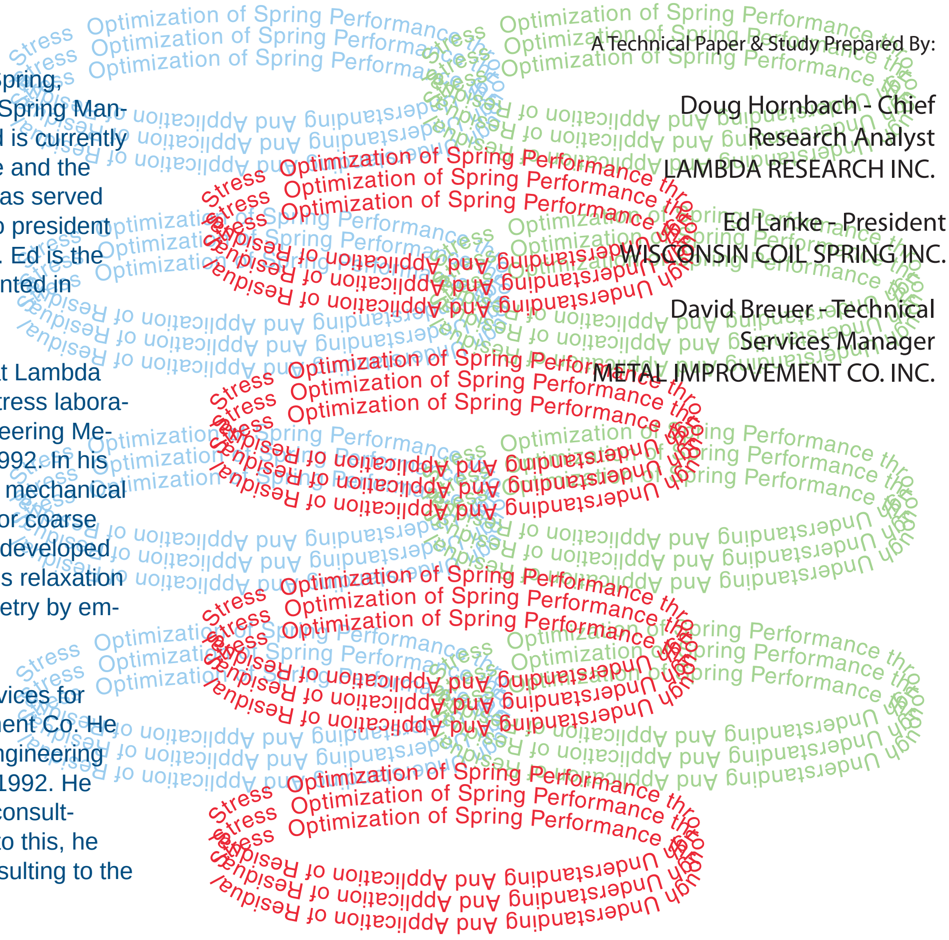
OPTIMIZATION OF SPRING PERFORMANCE THROUGH UNDERSTANDING AND APPLICATION OF RESIDUAL STRESS



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INTRODUCTION

The intent of this paper is not to present a new technology available to springmakers and spring users. The intent of this paper is to utilize existing spring manufacturing and analysis techniques to further the understanding of how a spring's fatigue performance can be enhanced and/or changed by modifying residual stress levels.

The three technologies used in this paper are not new technologies. Spring coiling, shot peening, and x-ray diffraction have all been around for decades. When the three are used interactively, along with scanning electron microscopy (SEM) and fatigue testing, the end result is a closed loop of theory supported by actual physical evidence. This is shown in the form of residual stress graph profiles and actual fatigue data proving or disproving proposed theory.

Critical to this study is the understanding and modifying of residual stresses to determine fatigue performance of coiled springs. It was also hoped that new information would be unveiled through extensive use of X-ray diffraction throughout the manufacturing of the springs. The following spring manufacturing techniques are examined and explained with the tools explained in the previous paragraph.

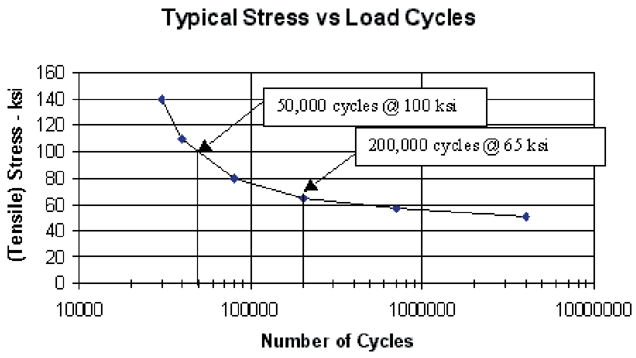
- Standard/Control Springs
- Single Shot Peened Springs
- Double Shot Peened Springs
- Dual Shot Peened Springs
- Superfinished (without shot peening) Springs
- Shot Peened & Superfinished
- Strain Peened Springs

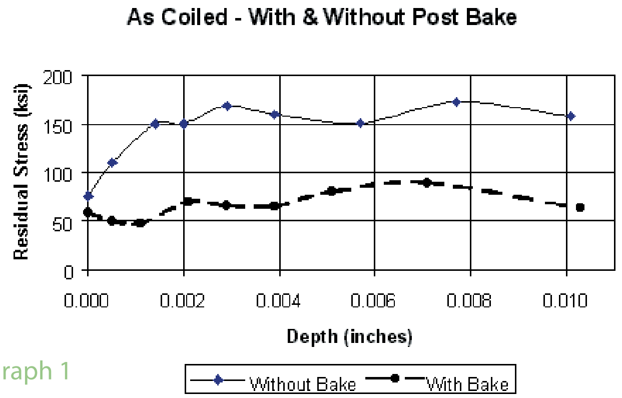
EXPLANATION OF TOOLS

Spring Coiling

The spring industry is representative of many manufacturing environments today. There are increasing demands on part engineering, performance, tolerances and quality. Often the spring is one of the last parts designed in an assembly. This means there is often limited geometry and high expectations of part life.

For spring makers to meet these demands they have to rely on tried and true practices along with incorporating secondary processes and analysis techniques. Shot peening,





Graph 1

X-ray diffraction, and superfinishing will be covered in detail throughout thisis often limited geometry and high expectations of part life.

For springmakers to meet these demands, they have to rely on tried and true practices along with incorporating secondary processes and analysis techniques. Shot peening, x-ray diffraction, and superfinishing will be covered in detail throughout this paper. Spring makers must know when to used these secondary processes and how it will affect their end product.

One of the basics of coiling is to incorporate baking operations throughout the manufacturing process. This is because most any process induces various levels of residual stress into a spring. This area is examined thoroughly in this paper through the use of X-ray diffraction.

A baking operation will partially neutralize the highest stresses of any operation which will reduce chances of material cracking (especially for Chrome - Silicon wire) and minimize changes in load either immediately or after a period of time known as “taking a set.” This study of a Chrome - Silicon spring wire utilizes two baking temperatures; 550^{O}Farenheit immediately following coiling and 400-450^{O}F following shot peening operations. Temperatures above 450^{O}F will begin to relieve out beneficial compressive stresses from shot peening.

One notes that the shot peening operation, though extremely beneficial for increasing fatigue properties, makes holding spring tolerances more difficult. Typically, one can expect an approximate 3% decrease in spring load following shot peening. In addition, the load variation is greater following the shot peening operation. These factors must be taken into consideration when meeting customers’ demands of increased fatigue life and tighter tolerances.

Customers who purchase springs should know that these changes can be expected with shot peening. Generally springs with load tolerances of 5%, 7.5%, and10.0% become difficult to make when shot peening is added. These increased tolerances with shot peening can result in additional material cost and production time which will negatively impact profit margins. If possible, the widest spring load tolerances should be utilized when shot peening is incorporated. A springmaker can then take this into account when designing and making the springs. For example, if a spring maker receives a load tolerance of ±12.5%, he will design his manufacturing process with a ± 10% load tolerance to fall within the 12.5%.

Aside from baking and accounting for load changes associated with manufacturing and shot peening, the spring maker needs to deliver a product free from rusting. To accomplish this, carbon steel springs should be lightly oiled following shot peening. Stainless steel springs should be passivated after the shot peening post bake operation.

Shot Peening

Shot peening is a cold working process used to increase the fatigue properties of metal components. During the peening process, the surface of the component is showered with many thousands of small, spherical pieces of media called shot. Each piece of media acts as a tiny peening hammer leaving the surface stressed in residual compression. When controlled properly, all surface area, which is susceptible to fatigue crack initiation, is encapsulated in a uniform layer of compressive stress.

The compressive stress is formed as a result of the impact of the media with the surface of the spring. During impact, the localized surface area of spring is stretched beyond its yield point in tension. After the media rebounds away, the surface tries to restore itself by pushing out the impacted area. This cannot take place because mechanical yielding has occurred which results in a “dimple” surrounded by compressive stress.

The amount of residual compressive stress from shot peening is directly related to the reduction of the applied tensile stress, which can cause fatigue failure. Hence, more compressive stress results in greater improvements in fatigue properties. This is especially important since fatigue life is plotted as tensile stress on the vertical axis (on a linear scale) and life cycles on the horizontal axis (on an exponential scale). This means a linear decrease in tensile stress translates to an exponential increase in fatigue life. This is shown in the graph to the left commonly known as an S-N curve. Please note that it is not representative of any material.

What is important to note in this graph is that at lower tensile stress levels, particularly the 50 ksi range, the life of the spring approaches infinity as 10 million or more cycles can be expected. The goal of shot peening, as stated before, is to induce compressive stresses to lower or offset the tensile stresses which cause fatigue failure.

Located to the right are many residual stress profiles (graphs) which were generated by the use of X-ray diffraction. These are plots of residual stress (tensile and/or compressive) versus depth from the surface. The three important variables (when shot peening is applied) are the surface compressive stress, maximum compressive stress, and depth of compression. This surface compressive stress is the stress at a depth of 0.000” or the very outermost surface layer. The next important variable is the maximum compressive stress which occurs .001” - .002” below the surface. The final variable is the depth of the compressive layer which is where the residual compressive stresses convert to residual tensile stresses. The subsurface tensile stress is a result of the previous forming operation and re-static balancing of the near surface compressive layer.

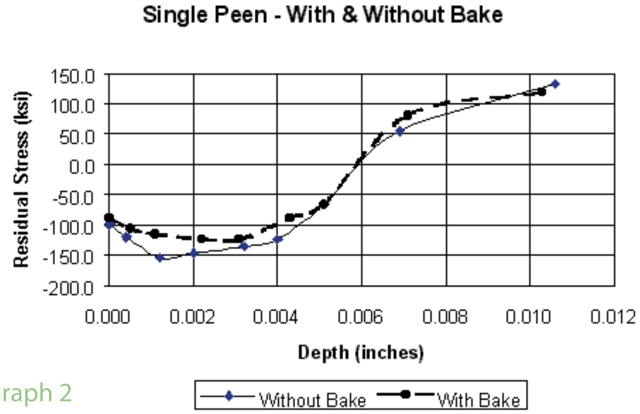
X-Ray Diffraction

X-ray diffraction (XRD) is the most accurate and best developed method for quantifying residual stress due to various mechanical/thermal treatments such as bending, coiling, shot peening, welding, machining, various finishing operations, etc., and offers several advantages over other methods, such as mechanical, ultrasonic or magnetic techniques. XRD is a linear elastic method in which the residual stress in a material is calculated from the strain in the crystal lattice. The theoretical basis and explanations are discussed elsewhere.(1) XRD can be employed to quantify the residual stress as a function of depth to thousandths of an inch below the surface, with high resolution due to the shallow penetration of the x-ray beam. XRD techniques are well established, having been standardized and developed by both the SAE(2) and the ASTM(3,4).

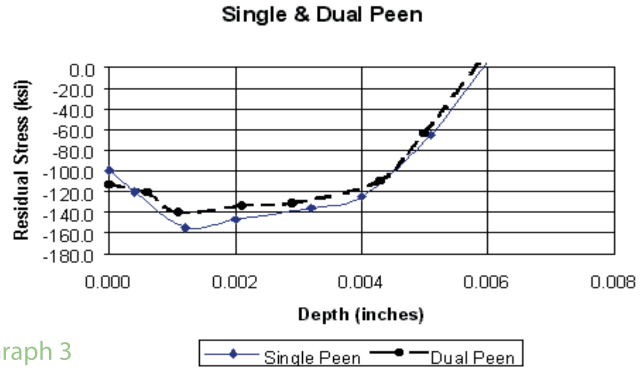
XRD methods have been used for many years in the aerospace, automotive and nuclear industries to quantify residual stresses and are employed in quality control applications to verify and confirm specific levels of compressive stress on shot peened components. As engineers rely more on residual stresses to increase the performance of components, it is necessary to understand and control residual stress levels.

In order to determine the residual stresses as a function of depth for this test study, XRD residual stress measurements were obtained in the direction parallel to the spring wire axis at the surface and at nominal depths of 0.5,1, 2, 3, 4, 5, 6, 7, and 10 x 10^{-3} inches (mils) into the wire. These depths were chosen to best define the residual stress distribution due to coiling, baking, shot peening, and superfinishing. The residual stress measurements were made at mid-length of each coil on the inside diameter. The inside diameter position was chosen because failures typically initiate on this location for compression springs.

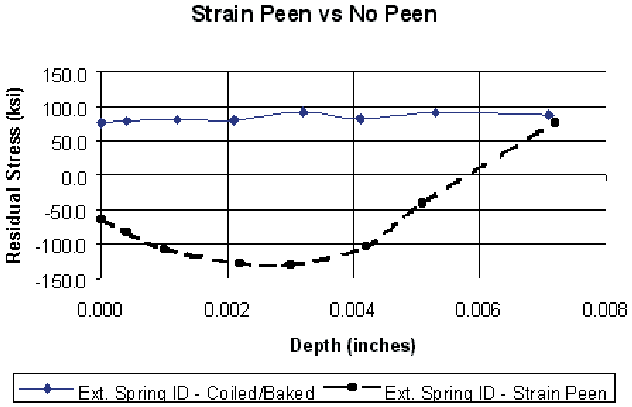
X-ray diffraction residual stress measurements were made by the two-angle $\sin^2\Psi$ method per SAE J784a.(2) Multi-angle measurements were obtained at 10 x 10^{-3} inches below the surface on the Standard/Control springs to verify a linear dependence of lattice spacing vs. $\sin^2\Psi$. The results show a linear response of lattice spacing vs. $\sin^2\Psi$, indicating a condi-



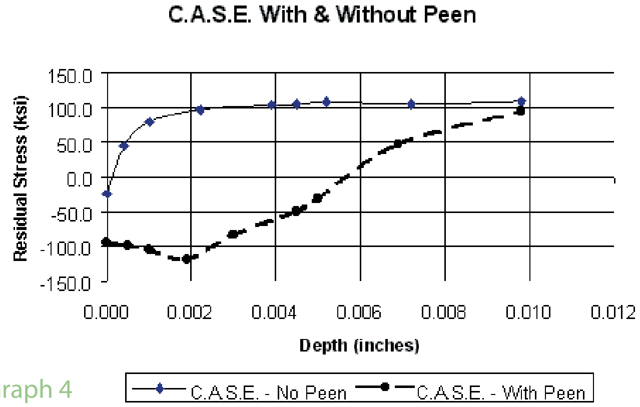
Graph 2



Graph 3



Graph 5



Graph 4

tion of plane stress at the surface, appropriate for XRD methods. Measurements were made employing the diffraction of chromium K-alpha radiation from the (211) crystallographic planes of the BCC structure of the Cr-Si steel. The diffraction peak angular position at each psi tilt was determined from the position of the K-alpha 1 diffraction peak separated from the superimposed K-alpha doublet assuming a Pearson VII function diffraction peak profile in the high back-reflection region(5). The diffracted intensity, peak breadth, and position of the K-alpha 1 diffraction peak were determined by fitting the Pearson VII function peak profile by least squares regression after correction for the Lorentz polarization and absorption effects and for a linearly sloping background intensity.

Prior to the X-ray diffraction measurements, a 90° segment of each coil spring was removed from mid-length of the coil in order to provide access for the incident and diffracted x-ray beams. A high speed aluminum oxide cutting wheel was used to section the 90° segment. During sectioning, the spring was subjected to a mist coolant spray to ensure minimal heat input from the cutting wheel. Stress relaxation at the measurement location due to sectioning was assumed negligible. The XRD measurement location was nominally two diameters from the cut end in order to minimize edge effects.

A .040” x .080” irradiated area (long axis parallel to the spring wire axis) was used on the sample surface in order to minimize error due to the curvature of the spring wire. The radiation was detected employing a scintillation detector set for 90% acceptance of the chromium K-alpha radiation.


Pict. 1. Compresson and Extension Springs used in the Study.

The value of the x-ray elastic constant, E/(1 + v), required to calculate the macroscopic residual stress from the strain measured normal to the (211) planes of Cr-Si steel was previously determined empirically(6) by employing a simple rectangular beam manufactured from Cr-Si steel loaded in four-point bending on the diffractometer to known stress levels and measuring the resulting change in the spacing of the (211) planes in accordance with ASTM E1426-94.(4)

Material was removed for subsurface measurement by electropolishing a nominal .200 x .100” pocket on the inside diameter of the coil in a phosphoric-sulfuric acid base electrolyte solution. The electropolishing minimizes the possible alteration of the residual stress distribution as a result of material removal. All macroscopic residual stress data obtained as a function of depth were corrected for the effects of penetration of the radiation employed for residual stress measurement into the subsurface stress gradient.(7) Stress relaxation due to layer removal was corrected by employing the method of Moore & Evans,(8) assuming the specimen behaved as a flat plate in the area which was electropolished. The higher the stress and the greater the depth of removal, the larger the relaxation will generally be. Finite element methods could be employed for a more rigorous layer removal correction if greater depths were investigated.

Systematic error due to instrument alignment was monitored employing a powdered iron zero stress reference sample. The measured residual stress in the powdered iron sample was found to be within ±2 ksi of zero stress.

The microscopic residual stress was determined during the macrostress measurement by measuring the full width at half maximum intensity (FWHM) of the (211) diffraction peak in the psi = 10° orientation. The (211) diffraction peak width is a sensitive function of the chemistry, hardness, and the degree to which the material has been cold worked. In martensitic steels, it is commonly observed that plastic deformation produced by processes such as shot peening or grinding will cause work softening and a reduction in the peak width. In work hardening materials, the diffraction peak width increases significantly as a result of an increase in average microstrains and the reduced crystallite size produced by cold working. Empirical relationships between cold work or hardness and peak broadening for several nickel base, titanium and steel alloys have been determined. No calibration curves were obtained to define such a dependence for the Cr-Si steel peak breadth investigated in the present analysis.

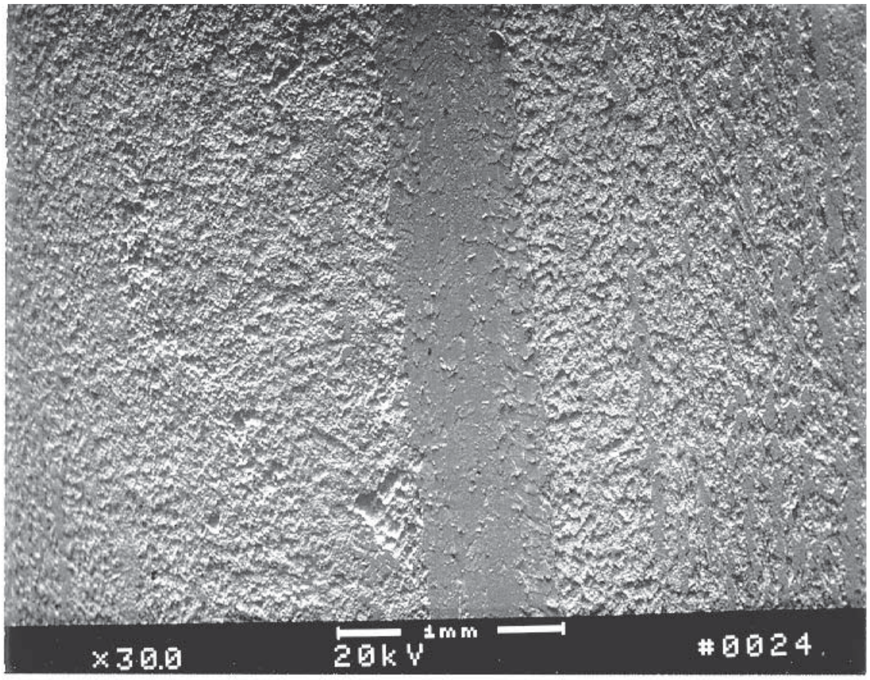
RESULTS OF MANUFACTURING TECHNIQUES

The compression spring selected for this technical study was designed with an expected cycle life of less than 100,000 cycles with a plain finish and no shot peening. These are the Standard/Control springs described in the next section.

From this Standard/Control spring lot, separate lots were created such that the other evaluated spring manufacturing types (listed in the Introduction) were all from the same heat lot of (Cr-Si) spring wire. In addition, the extension springs used in this study were from the same heat lot of wire.

The spring wire used for this study was a nominal .250" diameter oil tempered Chrome-Silicon. The spring wire had a nominal ultimate tensile strength (UTS) of 260 ksi. Picture #1, opposite page, is the compression spring (free length of 5.21") used for most of the study and the extension spring used for a portion of the study. Additional technical information on the spring and/or wire is listed in Appendix A.

The main goal of the XRD measurements was to determine variations in the residual stress produced by the different manufacturing processes such as coiling, peening and thermal exposure. By obtaining the residual stress and fatigue life data for the different manufacturing processes, a relationship between residual stress and fatigue life for coil springs can be developed. Once the relationship of residual stress and fatigue life are established for a specific spring, the residual stress state can be optimized to obtain maximum fatigue life.



Pict. 2. S.E.M. Photo at 30x Magnification Showing the I.D. of the Compression Spring and the Tooling Mark Left from the Forming Operation.

Standard/Control Springs

The Standard/Control springs were a lot which was coiled, baked at 550 degrees Fahrenheit immediately after coiling and then ground. Picture #2, above, is a S.E.M. photo (courtesy of Metallurgical Associates; Wauke-sha, WI) at 30 times magnification which shows the ID of the compression spring and the tooling mark left from the forming operation. One can see that how tears or scratching (not present in this photo) in this tool mark could act as initiation sites for premature failure.

Graph 1, page 112, shows two curves on one graph of the as-coiled condition without the required bake and the same spring wire with the post bake. One can see how the detrimental tensile stress levels reach almost 170 ksi without the 550^{O}F bake. With this magnitude of residual tensile stress, the ID runs the risk of cracking if baking is not done immediately.

It should be noted that the residual tensile stresses formed on the ID of the spring are created as it is coiled from yielding of the ID in compression as the ID is pinched while the OD is stretched. This mechanism is essentially the opposite mechanism of how the compressive stresses are formed from shot peening. The post bake reduces the tensile stress by over 100 ksi at some depths which is significant in terms of fatigue life.

The "As Coiled and Baked" springs were tested for spring load and also fatigue tested. This data is considered the control from which the other manufacturing techniques will be compared with. Please note the following results:

- Spring Load: 405.5 lbs at a length of 3.25"
- Fatigue Test: 80,679 cycles (average of 4 spring failures) with a 1.25" working stroke. The oscillating stress ranged from a calculated 50 ksi and 137 ksi. Additional fatigue test parameters are listed in Appendix B.

(Single) Shot Peened Springs

Using the control lot of springs, a number of springs were then shot peened using a 0.023" diameter media to a 16 - 20 A intensity. Picture #3, opposite page, is a S.E.M. photo (courtesy of Metallurgical Associates; Waukesha, WI) at 30 times magnification of ID of the coil. One notes it as being uniformly "dimpled" from the peening process. In addition to inducing a compressive layer onto the surface of the spring, the tooling mark present in the previous S.E.M. photo has been obliterated eliminating the most likely crack initiation site.

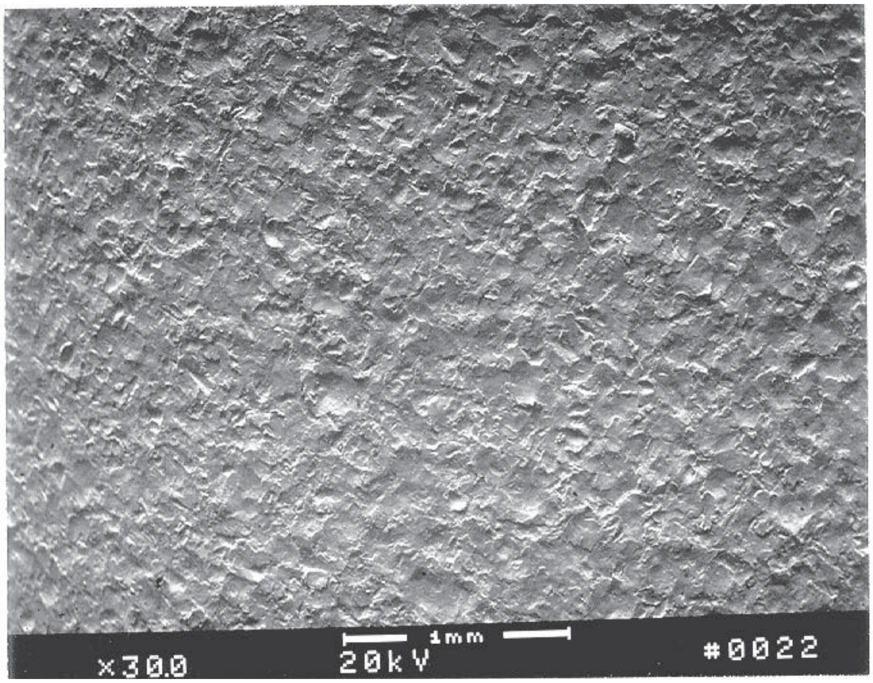
Graph #2, page 113, shows two curves for the (single) shot peened spring. One with the 400^{O} F bake following shot peening and one without the bake. Please note the baking after shot peening is 400^{O}F versus 550^{O}F for coiling. One notes that the residual stresses without the bake are reduced slightly in both the compressive layer and tensile sub layer. This would be expected as the baking operation would slightly relieve residual, compressive stress levels.

The maximum compressive stress is ~ .002" below the surface and has a magnitude of ~ 125 ksi after the bake. This is a tremendous reduction in tensile stress versus the residual tensile stress present in the "Standard/Control" spring. The reduction of tensile stress is ~ 150 ksi at the surface and ~ 195 ksi at .002" below the surface. Fatigue testing showed 1,000,000 cycles with no failures at which point the test was stopped due to time constraints.

It is important to note that the higher cycle the fatigue prior to shot peening (hence less net tensile stress), the greater the percent improvement in fatigue life. This is because lower cycle fatigue is on the left of the S-N curve shown before. The curve is much more vertical at this point which means less movement on the horizontal axis with a given reduction of tensile stress. This same spring had it only acquired 30,000 cycles without shot peening may have only obtained 90,000 cycles with shot peening. This is a 300% improvement versus the minimum 1,000% demonstrated in fatigue testing this spring.

The (single) shot peened springs were fatigue tested and also tested for spring load. Please note the following results.

- Spring Load: 400.7 lbs at a length of 3.25”
- Fatigue Test: 1,000,000+ cycles (No failures recorded with 4 springs tested) with a 1.25” working stroke. The oscillating stress ranged from a calculated 50 ksi and 137 ksi. Additional fatigue test parameters are listed in Appendix B.



Pict. 3. S.E.M. photo at 30x Mag. of ID of the Coil

Double Shot Peened Springs

When the fatigue life of a single shot peened fine wire spring is still in adequate, shot peening a second time with identical peening parameters (Double Peening) has been found to increase the number of cycles before failure will occur. The smallest steel shot media is .007” in diameter and the wire diameter being shot peened should be at least four times the shot diameter. Please note the importance of baking after each shot peening operation discussed previously.

It may also be necessary to limit the lot size in order to get adequate peening coverage. An example would be a 300,000 piece order that would be shot peened in three 100,000 piece lots for insurance of maximum coverage. A possible reason for the increase in fatigue life of with Double Peening is the “homogenizing” effect that takes place when the parts are thoroughly mixed. This happens when they are transferred from the first shot peen operation to the baking baskets and then to second shot peen operation which is then baked a final time. Time constraints prevented fatigue testing.

- Spring Load: 395.6 lbs at a length of 3.25”
- Fatigue Test: Not performed at this time.

Dual Shot Peened Springs

The purpose of dual peening is to increase the compressive stress at the very surface fibers (depth = 0.000”) with a secondary peening operation. By further compressing the top surface fibers, initiation of a fatigue crack becomes more difficult. The dual peen was performed with an .011” diameter shot at an 8 - 10 A intensity. Since this is a lower intensity, there will be no change to the depth of the compressive layer. It would take a greater intensity, which has more energy to drive in a deeper depth of compression. It was performed to a batch of (single) shot peened springs following the initial post shot peening bake at 400^{O}F.

The reason that dual peening increases the surface compressive stress is that this magnitude is a function of the disruption or dimpling of the surface. A properly shot peened surface has a uniform dimpled appearance. The surface consists of high points and lower plateaus. These are the result of the surface material being pushed around as the peening media impacts it. A more aggressive peening operation (higher intensity) will result in larger dimples. The high points are less compressed than the lower plateaus.

The secondary peening operation is done with a smaller diameter media. The smaller media is able to further compact the high points left from the first peening operation. The dual peening leaves another uniformly dimpled surface, but the high points are smaller than the first peening operation. This results in a finer surface finish and a more compressed top surface layer.

Picture #4, page 117, is a S.E.M. photo (courtesy of Metallurgical Associates; Waukesha, WI) which shows the ID of the coil (30x magnification) following dual peening. The surface finish is less aggressive, having more dimples which are smaller in size than the previous photo of a single shot peened spring.

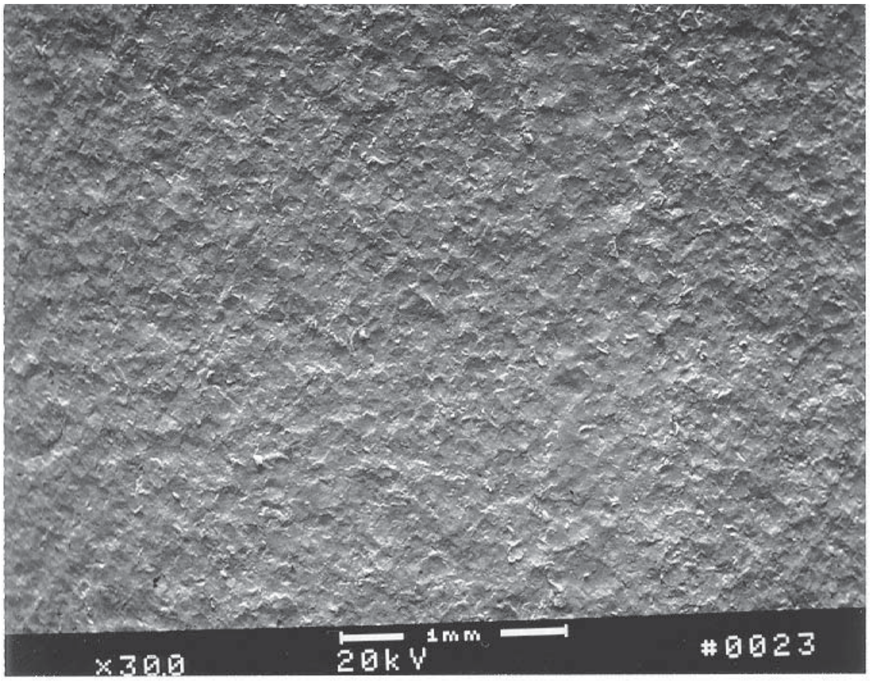
Graph #3, page 113, in shows two curves. One curve shows the compressive stress from single shot peening and the other shows the dual peening. It should be noted that the surface (depth = 0.000”) is compressed ~ 14 ksi further with the dual peening process. Due to time constraints, fatigue testing was not performed to the dual peened springs.

What is interesting to note is that the curves should be identical (as they are the same material from the same heat lot) with the exception of the compressive stress at the outer surface. The depth of the compressive layers match very closely (~ .006”), but there is a difference in the maximum compressive stress by approximately 15 ksi. It is not known what test factors contributed to this difference.

If the dual peened curve were lowered by approximately 15 ksi from the outer surface to .002” below the surface (to make the max. compressive stress levels match) the increase in the surface stress is closer to 29 ksi than the 14 ksi shown on the data tables.

One could probably expect a noticeable increase in fatigue life with dual peening. This applies to a 14 ksi increase (and more so for a 29 ksi increase). This is providing the single peening results are in the high cycle fatigue range. One notes in the S-N curve that the high cycle fatigue portions of the curve have very large increases in fatigue properties with drops in tensile stress. Spring load checks for the dual peening yielded the following:

- Spring Load: 397.6 lbs at a length of 3.25”.
- Fatigue Test: Not performed at this time



Pict. 4. S.E.M. photo at 30x Mag. Showing the I.D. of the Coil Following Dual Peening.

Superfinished (without shot peening) Springs

It is a well known fact that surfaces that are subject to fatigue failure perform better when they have better surface finishes. This is because a better surface finish has fewer locations and smaller stress risers for fatigue cracks to initiate.

For this technical study, two sets of springs were superfinished. The superfinishing was actually Metal Improvement Company’s C.A.S.E.^{SM} process. This is an acronym for Chemically Assisted Surface Engineering and is primarily applied in situations where both fatigue and contact/pitting failures are a concern. The process is a vibratory honing process performed in a chemical solution to accelerate the process. A good example is gearing for racing applications.

The superfinishing was included as part of this study because it is believed there have been no studies performed on spring performance and this type of process. Two lots of springs were superfinished. One lot was the as-coiled condition and the other lot was performed after (single) shot peening.

Picture #5, opposite page, is a S.E.M. photo (courtesy Metallurgical Associates; Waukesha, WI) which shows the ID of the spring after superfinishing (at 30x magnification). The residual stress levels are discussed in the following section. One can see some of the remains of the original tooling mark. Visually the springs have an attractive, mirror finish as shown in Picture#6, page 119.

A batch of these springs was fatigue tested. The results show that an average of 81,100 cycles happened before failure under the same test as the Standard/Control springs. When comparing this to the Standard/Control springs, they have almost identical fatigue lives. This is good proof that these fatigue failures can be attributed to the residual tensile stresses present on the ID from coiling more so than the tooling mark as a result of the coiling.

The graph showing the residual stress levels from this process is described in the next section. Please note the test results from the Superfinished (only) springs.

- Spring Load: 403.1 lbs at a length of 3.25”
- Fatigue Test: 81,100 cycles with a 1.25” working stroke.

Shot Peened & Superfnished Springs

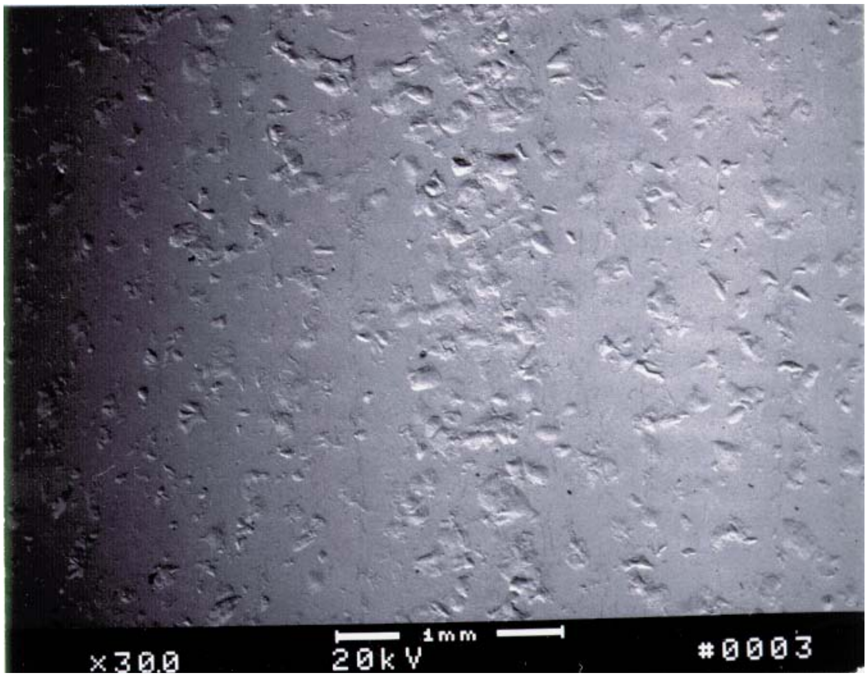
The C.A.S.E.^{SM} process described in the previous section is normally performed following shot peening. The uniform, stock removal from the vibratory honing process removes several tenths of a thousandths of an inch. (~ .0001” - .0003”) depending on the material, hardness and processing time.

Recall this outer location of the surface is less compressed than slightly below the surface. Since shot peening leaves a very even, uniform surface finish, the superfinishing works very well following shot peening.

Visually, the springs have the same mirror finish (Picture #6, opposite page) whether shot peened or not prior to the superfinishing. Graph #4 shows the difference in residual stresses of both springs. It should be noted that both the surface and below the surface the stress levels are in much more of a compressed state with the shot peened spring.

There is ~ 70 ksi more compressive stress at the surface and ~ 223 ksi more compressive stress just below the surface. Please note the extremely shallow compressive layer on the non-shot peened spring which would offer little fatigue protection. This is because only .0001" - .0003" of stock was removed from the Standard/Control springs which had much deeper, residual tensile stresses with very high magnitudes. This is why the Superfinished spring without prior shot peening performed the same as the Standard/Control springs.

For these reasons one could expect superior fatigue performance from a C.A.S.E.^{SM} processed spring with prior shot peening. Fatigue testing was performed and stopped at 1,000,000 cycles with no failures. Though fatigue testing wasn't completed, one would anticipate results to be better than a (single) shot peened spring and similar to (or better than) the dual peened springs,which were not fatigue tested.



Pict. 5. S.E.M. Photo at 30x Mag. Showing the I.D. of the Spring After Superfinishing.

- Spring Load: 396.4 lbs at a length of 3.25"
- Fatigue Test: 1,000,000+ cycles (No failures recorded with 4 springs tested) with 1.25" working stroke.

Strain Peened Springs

Strain peening is a type of peening in which the part is physically loaded prior to shot peening. The intent is to increase the magnitude of the maximum compressive stress. This, again, is the value of the compressive stress at .001" - .002" below the surface. This value is a function of the base material properties and should be the same regardless of the (non-strain peened) shot peening parameters. The theory as to how this happens with strain peening is as follows:

Using traditional shot peening, the compressive stress is formed from the impact of the media stretching the surface beyond its yield point in tension. With strain peening, the part is loaded such that there is a tensile stress on the surface prior to shot peening. When the media impacts the surface, the surface yields further in compression from both the impact and physical loading. This results in a greater maximum value of compressive stress.

For this technical study, a lot of extension springs were coiled and baked from the same heat lot of spring wire as the compression springs. Extension springs were chosen because they are much easier to apply a load to for strain peening. The springs were stretched 1.125" for the shot/strain peening. This allows enough room for the shot to travel through the coils to peen the ID. They were peened to the same intensity as the compression springs (16 - 20 A). Graph #5 in Appendix A shows an extension spring that was strain peened (with post bake) along with another extension spring (with bake) after coiling with no shot/strain peening.

What is interesting to note in Graph #5, page 113, is that the magnitude of the maximum compressive stress is almost identical to the (single) shot peened springs when it was expected to be higher. This is not necessarily true. What one must look at more closely is that the coiling of the extension springs (after bake) induced ~ 20 - 30 ksi more residual tensile stress than the Standard/Control springs (with bake). This means the strain peening had to induce 20 - 30 ksi more compressive stress such that the results would be very close to the (single) shot peening.

One could expect significant fatigue improvements with strain peening over conventional shot peening, dual peening, or superfinishing. Please note though that there is the most significant decrease in spring load with strain peening to accompany this excellent improvement. The reason for the significant improvement is that both the surface stress and maximum compressive stress are increased by 20 - 30 ksi rather than just the surface stress with dual peening.

It should be noted that strain peening of springs is not a common practice. The main reason is that it is cost prohibitive due to the labor and fixturing required to stretch the springs for shot peening.

For comparison purposes, spring load inspections were taken at an extension of 6.76" to a non-shot peened, conventional shot peened, and strain peened extension springs. One notes a large drop in spring load with the strain peened spring.

- Spring Load, No Shot Peening: 180.2 lbs at a length of 6.76"
- Spring Load, Conventional Shot Peening: 175.9 lbs at a length of 6.76"
- Spring Load, Stain Peening: 160.8 lbs at a length of 6.76"
- Fatigue Tests: Not performed at this time.

Appendix A - Additional Spring & Wire Data

- Material: Oil Tempered Chrome Silicon Wire in accordance with ASTM-A-401-93
- Wire Diameter: 0.250”
- Tensile Strength: 258.5 - 262 ksi
- Free Length: 5.207”(calculated)
- Outer Diameter: 2.000” (.040”
- Active Coils: 5.18 (calculated)
- Total Coils: 7.18 (calculated)
- Spring Rate: 202.4 lbs/inch (calculated)
- Helix Angle: 9.39 Degrees

Pict. 6. Visually, the Springs Have an Attractive Mirror Finish.

AppendixB - Additional Fatigue Test Data

- For the fatigue test, 4 springs were cycle tested at 3.333 Hz (12,000 cycles/hour)
- The free length of the spring was 5.21”
- The upper displacement limit of the fatigue test was 4.50” which results in a calculated load stress of 49,500 psi.
- The lower displacement limit of the fatigue test 3.25” which results in a calculated stress of 137,000 psi.
- The 4 springs were placed in a fixture designed to insure equal loading around the center of the ram that actuated the test.
- Results of Standard/Control springs: 47,005 66,402
- Results of Superfinished (no shot peening) springs: 70,700 72,700 85,400 95,600 cycles.
- Results of (single) shot peened springs: No failures @ 1,000,000 cycles
- Results of Superfinised (with shot peening) springs: No failures @ 1,000,000 cycles

Appendix C- Acknowledgements

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- All spring design, materials, coiling, baking, load testing and fatigue testing: Wisconsin Coil Spring Inc., Mus-kego, WI (414) 422-2000.
- All shot peening & strain peening: Metal Improvement Co., Inc., Milwaukee, WI (414) 355-6119.
- All X-ray diffraction: Lambda Research Inc., Cincinnati, OH, (513) 561-0883.
- All Scanning Electron Microscopy Photographs: Metallurgical Associates Inc., Waukesha,WI, (414) 798-8098.
- All Super-finishing/Polishing: Metal Improvement Company Inc., Bloomfield, CT (860) 243-2220.

Appendix D -References

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