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Technical Article

SHOT PEENING SPRINGS

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Shot peening as a method of significantly improving the operating (fatigue) life of springs is by no means new. The commercial origins of the technique go back to the automobile industry of about 1930, and today almost all automobiles use shot-peened valve springs, and, in many cases, suspension springs. Shot peening has been applied successfully to springs with wire diameters as small as 0.010 in., as well as to extremely large coal pulverizer suspension springs with a diameter of 3.5 in. Peening is also used on a production basis on leaf springs, Belleville springs, and torsion bars.

The peening process is relatively inexpensive and has proven capable of increasing operating life by five to 10 times or more when compared to unpeened springs.

Tensile Stress is Major Problem

Metallurgical and design criteria are well covered in engineering courses and design texts, but mechanical treatment methods, such as the shot peening process, are rarely reviewed in sufficient detail. The result is that many springs designers do not fully understand the benefits to be expected from shot peening or the parameters to be specified to ensure repeatable quality of their springs.

A spring subjected to a large number of stress cycles frequently will fail sooner than anticipated by the designer. To assure sufficient operating life, as well as the load and deflection characteristics desired, a designer may select conservative physical dimensions. However, this conservatism in design can be costly in terms of material costs, weight, and space requirements, as well as size and weight of associated components. Any attempt to achieve a significant reduction in operating stresses, say 25 percent, results in an appreciable increase in wire diameter and doubles the weight (spring weight varies directly to the square of operating stresses). The high cost of material in comparison with the low cost of shot peening often dictates peening as the cost-effective approach.

Further, design engineers are currently giving extra consideration to product safety in view of the increasing product liability activity. Any reasonable means of increasing product reliability is low-cost insurance.

Causes of Fatigue Failure

The origin of fatigue failures in springs can usually be traced to surface defects and one of the major factors is often the severe residual stress created in the forming operation. Most of these stresses are tensile in nature and if they occur in critical areas which will be subjected to applied tensile stresses, catastrophic failure will occur. It is common practice to thermally stress relieve springs after forming to ensure complete stress relief — theoretically, the surface is at zero stress.

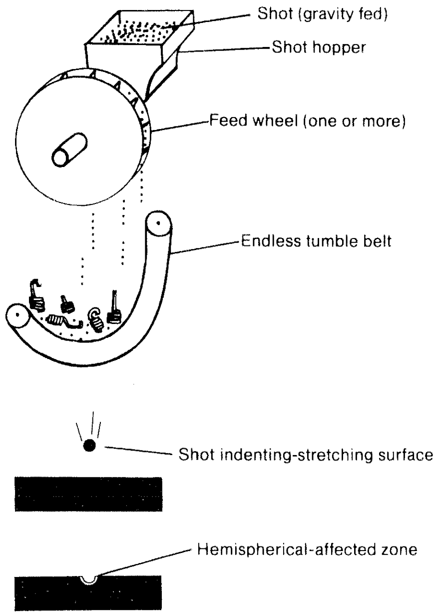


Fig. 1. Shot propelled by centrifugal wheel impacts spring surfaces to create a fatigue-resisting layer of compressive stress.

It is well known that most fatigue failures initiate at the surface as a crack and propagate under cycling until failure occurs. For these cracks to initiate, the surface must be in tensile stress and they will not propagate through a compressively stressed surface.

If a residual compressive stress is produced in the surface, the tensile stress created by the applied load must first overcome the residual compressive stress before the resultant surface stress becomes tensile. Therefore, a peened spring will live longer at design stress levels, or the same life can be achieved at higher stress levels (see fig. 2).

Shot peening is the most effective and inexpensive method to produce the desired residual compressive stress at the surface of a spring. This involves bombarding the surface with rounded particles propelled at high velocity (fig. 1), 200 ft./sec. or more. Each shot particle, with controlled shape and of uniform size, acts as a peening hammer to cold work the surface and produce compressive stresses.

A distribution of this compressive stress is shown in a typical peened surface with no external load applied (fig. 2). Because compressive stress has been produced at the surface, an offsetting tensile stress has been developed in the core. For the part to remain in equilibrium, the two areas in the region of compressive stress must be equal to the corresponding core area in the region of tensile stress. In other words, the sum of the moments around the neutral axis must equal zero.

When an external bending stress is applied (fig. 2), the resultant stress at any depth must equal the algebraic summation of the residual and applied stress (both shown as dotted lines). The resultant stress (solid line) defines the stress distribution through the section while under load. In this example, the surface remains in compressive stress even though the section is under load. If even higher stresses were applied, the resultant curve would shift to the left, perhaps into tensile stress. However, the resultant tensile stress will be far lower than if the surface had not been peened, or worse, if the surface was originally in tensile stress.

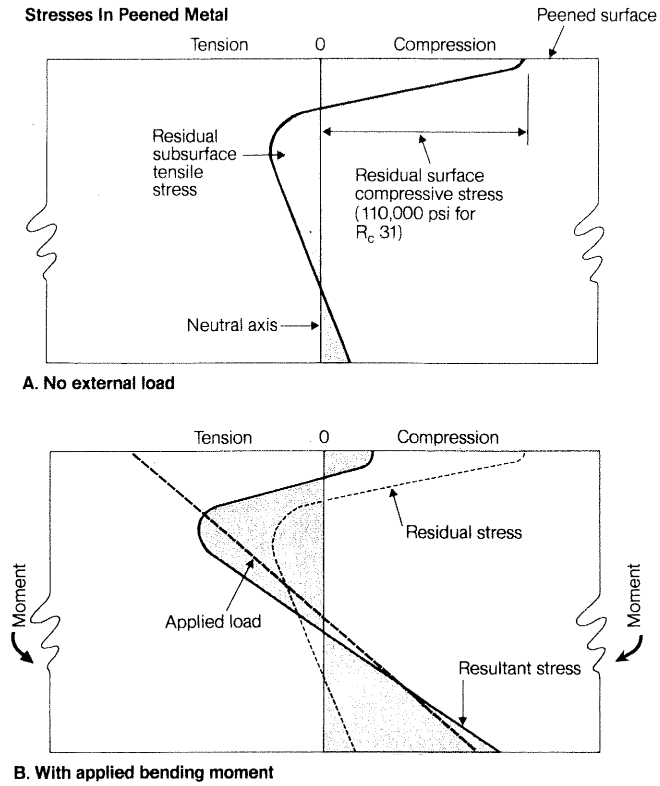


Fig. 2. Compressive stress induced in the peened surface of a shot-peened beam (A) prevents tensile stresses from occurring after a bending moment is applied to the part.

Gains in Operating Life

Much testing has been accomplished to determine the improvement in fatigue life of springs as a result of the shot-peening process. Referring to the chart based on tests with peened and unpeened automotive leaf springs (fig. 3), it can be seen that properly peened leaf springs, cyclically stressed to a level of 150,000 psi, live for over 1 million cycles. Non-peened springs have a maximum life of approximately 250,000 cycles.

Excellent improvements in fatigue characteristics have also been noted with helical springs wound

Table 1. Increases in fatigue strength in helical springs.

Description	Test duration millions of cycles	Fatigue strength Not peened	Fatigue strength Peened	Improvement
Music wire, 0.039 in. dia.	0.4	120,000 psi	190,000 psi	58%
Oil tempered, 0.207 in. dia.	10	85,000	120,000	41
Hot coiled 1095, ¾ in. dia.	2	60,000	90,000	50
Beryllium copper, 0.148 in. dia.	10	40,000	78,000	95
Stainless 18-8	10	80,000	120,000	50
S-816	10	55,000	100,000	81

from a variety of materials. Referring to Table 1, shot-peened music wire springs showed an increase in allowable operating stresses of 58 percent from 120,000 to 190,000 psi. Such increases in allowable operating stresses which average from 41-95 percent, as noted in the table, can lead to tremendous increases in operating life.

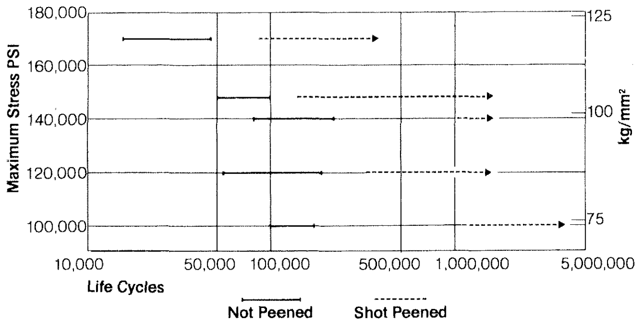


Fig. 3. Operating life tests on automotive leaf springs show dramatic increases in the life (cycles-to-failure) of shot-peened springs compared to the life of non-peened springs. Note that the life cycles are plotted logarithmically.

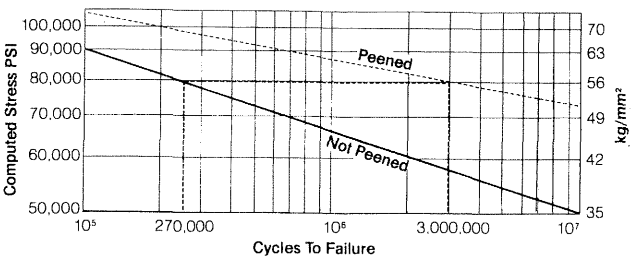


Fig. 4. Shot peening applied to surfaces exposed to high bending loads, such as carburized and hardened gear teeth, increased the life considerably. For example, the life of teeth subjected to loading of 80,000 psi increased from 270,000 cycles before shot peening to 3 million cycles after shot peening.

Figure 5 shows the allowable fatigue strength with and without shot peening on helical springs with a wire diameter of 0.207 in.

Variables in Shot Peening

Effective peening depends upon a number of variables such as type, hardness, and diameter of the shot used, nozzle pressure or wheel speed, duration of the peening cycle (coverage), and, in some cases, distance from the shot delivery system to the part, and impingement angle. To quantify and specify all of these variables would be too cumbersome to be practical. A method was developed

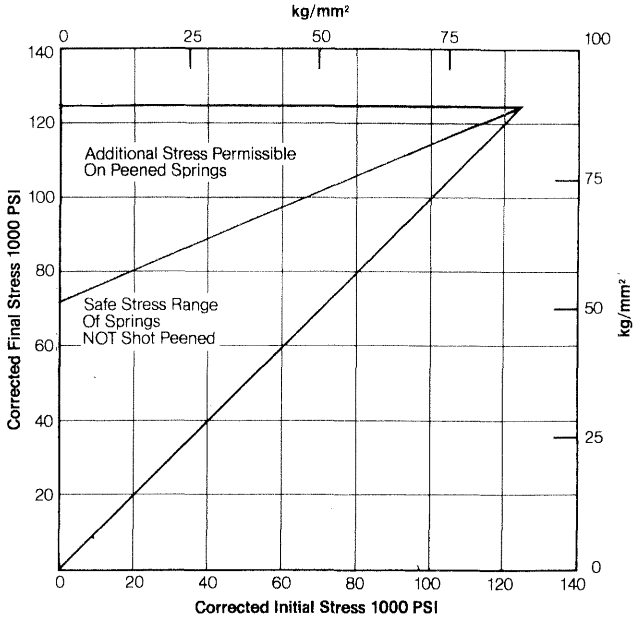


Fig. 5. Goodman diagram gives allowable (safe) values of fluctuating stress for various values of mean stress. The curves are for shot-peened and non-peened helical springs with wire diameter of 0.207 in.

many years ago by J. O. Almen for determining the intensity level being developed by a given peening set-up. This involves measuring the intensity, i.e., kinetic energy of the shot stream on a target location which simulates the critical surface.

When a flat strip of spring steel, an Almen strip, is clamped to a block and exposed to a stream of shot, it will be uniformly curved upon removal from

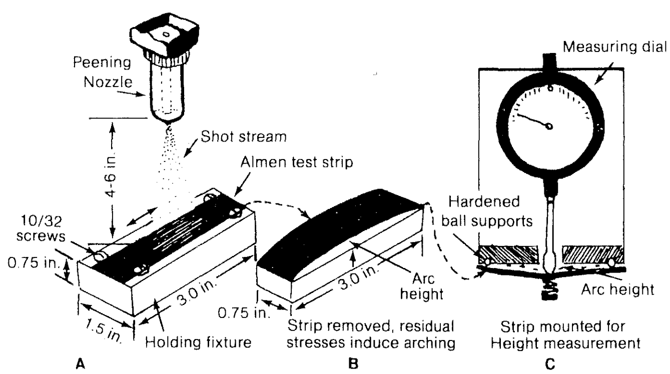


Fig. 6. To measure the intensity of shot peening, a standardized test strip (see fig. 7) is clamped to a holding fixture and exposed to a blast of shot. The amount of resulting arcing is a measure of peening intensity.

the block, due to the compressive stresses produced by the peening action (fig. 6). The curvature is convex on the peened side. The height of the arc serves as a measure of the kinetic energy of the peening operation and is referred to as intensity.

Three thicknesses of strips are used to provide for different ranges of intensities (fig. 7). The Almen A strip (.051 in. thick) is the one most commonly used

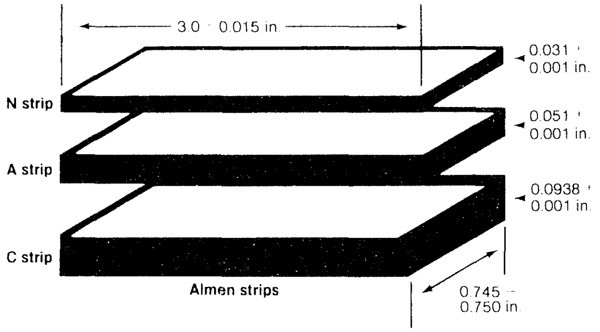


Fig. 7. Three sizes of flat test strips have been standardized for measuring, specifying, and duplicating shot-peened intensities. Of these Almen strips, the A-strip is most commonly used.

and relates to the intermediate intensity ranges. The Almen N strip (.031 in. thick) is used for lower peening intensities and the Almen C strip (.094 in. thick) is used for unusually high intensities. The height of the resulting arc on any of these strips will vary with shot velocity and time of exposure to the shot stream.

Saturation is said to occur when doubling the time of exposure and will not further increase the arc height by more than 10 percent (fig. 8). Regarding

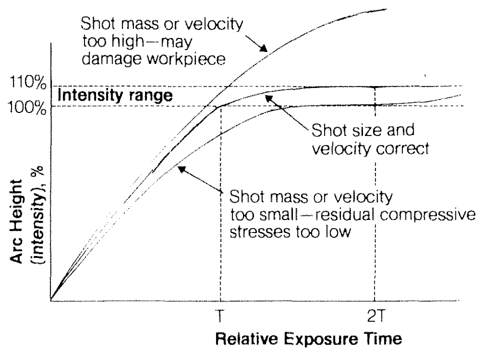


Fig. 8. By performing a series of Almen-strip tests and plotting the results, the shot mass and velocity used can be checked to assure producing good, uniform depth of compressive stress.

the curves, saturation occurs just beyond the knee of the curve. Development of this curve for any new part to be peened is important so that saturation occurs within the specified intensity range.

Quality and Type of Shot

Careful specification and determination of intensity is important and especially critical on fine wire springs. The intensity governs the depth of the compressive layer and it must be remembered that when residual compressive stress is developed on the surface, off-setting tensile stresses are developed below surface. If too deep a compressive layer is achieved, that is, greater than 25 percent of the cross-sectional area, the core tensile stresses can exceed allowable limits and distortion can occur.

Cast steel shot, commonly used for shot peening, is available in different degrees of hardness and the selection of shot hardness depends on the hardness of the material being peened. The regular hardness shot, usually 47-48 Rc, is suitable for peening materials with a hardness below 50 Rc. However, when peening harder materials, such as music wire, chrome vanadium, and chrome silicon, a harder shot, nominally 60 Rc, should be used (fig. 9). On

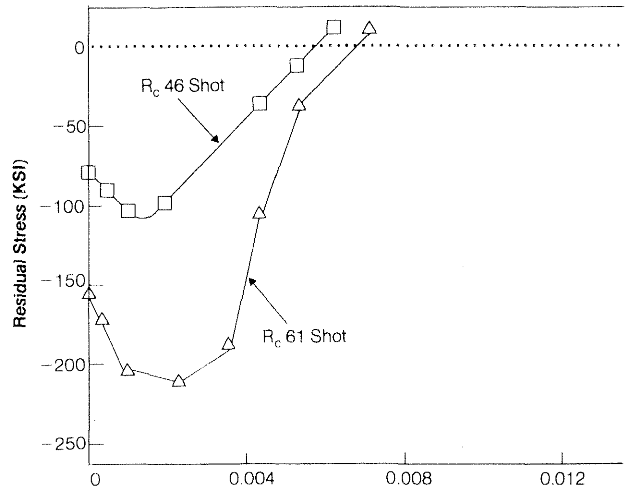


Fig. 9. Shot used for peening should always be at least as hard as the parts being peened. Greater magnitudes of compressive stress can be obtained by using hard shot on hard materials.

the harder materials, the special hard shot will result in a higher magnitude of residual compressive stress and, therefore, greater fatigue strength.

Most commercially available shot meets MIL-S-851 or ASM-2430 specifications. Metal Improvement Company recommends the use of shot meeting the requirements of MIL-S-13165B, "Shot Peening of Metal Parts," which requires close screening tolerances and shape control. For optimum peening results, it is not only recommended that shot be purchased to this specification, but that these tolerances be maintained throughout the processing cycle.

Due to repeated impacting against the hard parts being peened, the shot will fracture over a period of time. When this occurs to a nominal degree, the intensity will diminish, reducing the depth of compressive layer. In addition, the fractured particles have sharp edges so that they no longer function as a peening hammer, but more like a chisel. By means of shot classification equipment, the broken material can be removed and the uniform shot re-used. For best results, the spring designer should request certification that the shot peening was performed in compliance with MIL S-13165B.

Another important control factor is that of complete coverage. It is difficult in many cases to examine all surfaces of a peened spring with a magnifying glass to determine if full coverage was achieved. For example, it is extremely difficult to inspect the inside diameter (I.D.), the critical area for coverage, of a tightly wound compression spring having very narrow coil spacing, such as a fuel injector spring. A more practical and accurate method of inspection for coverage is the Peenscan process developed several years ago by the Metal Improvement Company (fig. 10).

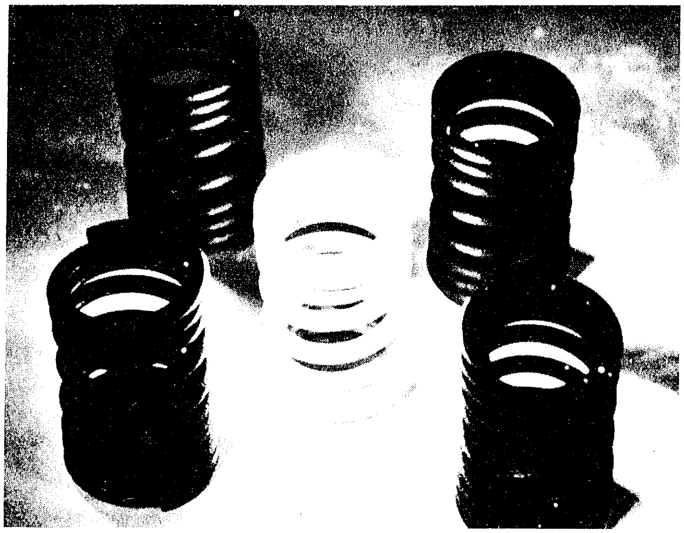


Fig. 10. Center spring is coated with Dyescan prior to shot peening. All Dyescan has been removed from the other four shot-peened springs, indicating full coverage.

The Peenscan process is recommended in MIL S-13165B (amendment 2, 1979) in lieu of visual examination. The critical area of the spring is coated with Dyescan, a dye that fluoresces under ultraviolet light. After this surface has been shot-peened and full coverage achieved, inspection under ultraviolet light should indicate no remaining traces of Dyescan. If this inspection indicates remaining Dyescan one or more of the peening parameters has changed, resulting in incomplete coverage.

Magnitude and Depth of Peening Stresses

Earlier in this article, we discussed some of the causes of fatigue failures in springs and the effect of residual forming stresses. Another common source of premature fatigue failure is that of surface defects, such as tool marks remaining from the forming operation. In many cases, it is difficult, if not impossible, to avoid these marks. When present, they represent notches or points of stress concentrations. Many fatigue failures initiate in these areas. In most cases, shot peening can negate the notch effect of these defects in one of three ways, depending upon the material and the nature of the defect. If the material is fairly soft (below 40 Rc) and the defect shallow, the peening effect will tend to blend the defect due to the plastic flow on the surface. On harder materials, care must be taken in selection of shot size and/or intensity, either using a fine shot which is small enough to peen the root of the "notch," or a larger shot and higher intensity to produce an adequate layer of compressive stress to extend beyond the depth of the discontinuity.

The depth of the compressive layer resulting from shot peening can be predicted using Figure 11 and is a function of the material hardness and the Almen intensity of peening. For example, to achieve a 0.010 in. depth of compressive layer in a material of 52 Rc hardness, an intensity of .017A would be required. Depths for hardnesses not shown can be interpolated.

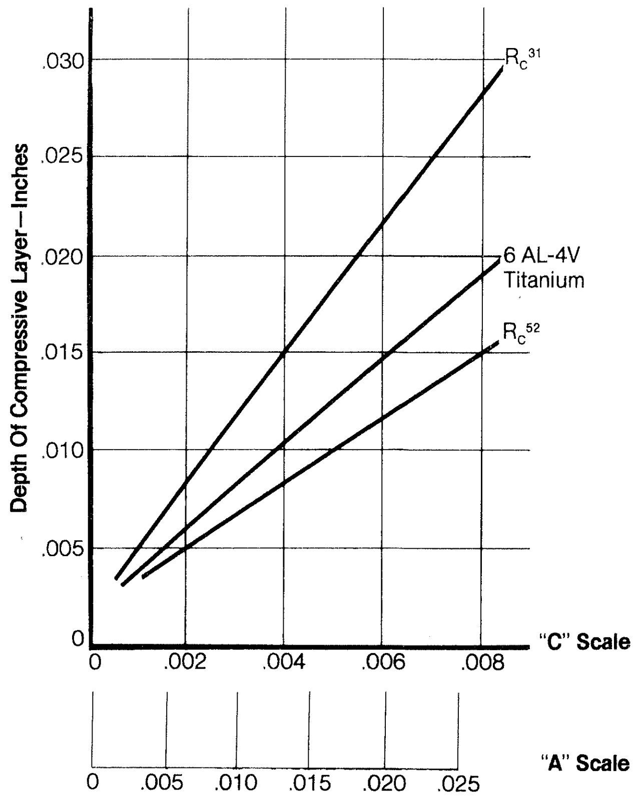


Fig. 11. The harder the material being peened, the shallower the depth of the compressive stress layer resulting from peening at a particular intensity (arc height).

The magnitude of the compressive stress can also be predicted as shown in Figure 12. In the case of 31 Rc, as shown, we would expect to achieve a residual compressive stress of approximately 110,000 psi.

Selecting Areas to Peen

It may not always be necessary to peen the entire surface of a spring. Many leaf springs are stressed in only one direction. Consequently, it is only necessary to peen the side subjected to tensile stress (fig.

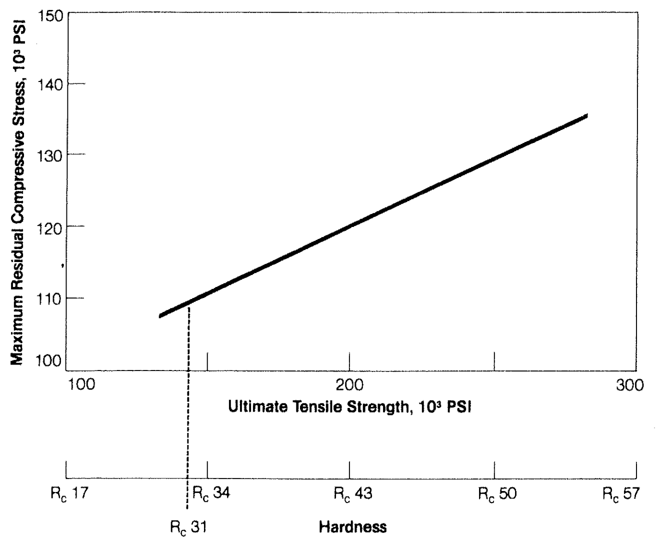


Fig. 12. The harder the material being peened, the higher the maximum compressive stress induced in the material. The chart is for shot peening using regular hardness 45-55 Rc shot.

13A). However, if the spring is to be stressed in both directions, it will be necessary to peen both sides (fig. 13B).

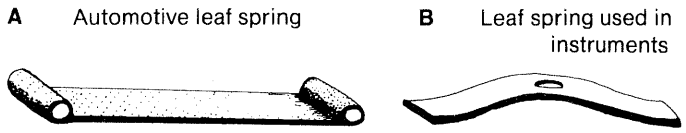


Fig. 13. **A**, Leaf spring stressed in one direction only; **B**, leaf spring stressed in two directions.

Torsion bars are generally peened over the entire surface unless they have a localized area for fatigue initiation. In this latter case, it is only necessary to peen the localized area. This limited and localized peening requirement is worthy of note as it may be possible to realize economies in the peening operation by limiting the area to be peened.

Peening the I.D. of some compression springs may require internal shot-peening equipment if it is not possible to deliver shot to the I.D. from an external source. A typical case involves a large, heavy-duty compression spring used as a jarring tool to dislodge a well-drilling bit when it becomes stuck in a hole far below the earth surface. This spring is machined from solid round stock to create coils with a rectangular cross-section, almost 1 in. thick.

When used in the field as part of a jarring mechanism, the springs experienced short life due to high shock loads that occurred when jarring the bit loose from the earth. Another factor that taxed the ability of the springs to resist failure was the highly corrosive hydrogen sulfide environment to which they were exposed.

To facilitate the peening process, a rotating lance-type nozzle is utilized which is oscillated throughout the entire I.D. With this method of peening, the I.D. of the spring receives uniform and complete shot peening resulting in 300 percent fatigue life improvement.

Stress Peening for High Stress Conditions

Conventional shot peening techniques will often result in benefits which will increase the fatigue strength or endurance limit of springs by 50 percent or more. However, in some cases, for various reasons, conventional peening may not be adequate. Redesign is one option, but this is often not possible because of space limitations.

However, in such situations specialized peening operations can be employed to achieve much greater improvement. One such operation is stress peening (fig. 14) in which each part is fixtured and prestressed in the direction of the operating load. Often, the prestress will be as high as 80-90 percent of the yield strength of the material. The part is then shot peened in this prestressed condition. While in the stressed condition, maximum tensile stresses are developed in the surface. When peened, the surface stresses are changed to compressive. When removed from the fixture, the part returns to its original state which adds to the surface compressive stress. Stress peening, which is used for some automotive leaf springs, will often result in several times the improvement of conventional peening.

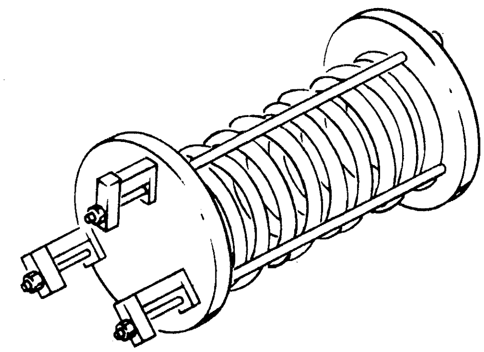


Fig. 14. Stress peening means loading in the direction of the applied load and shot peening while the spring is held.

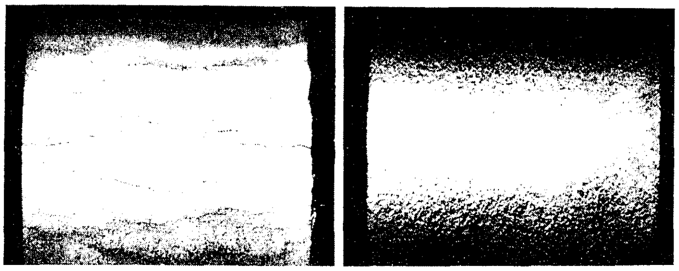
Stress-peened springs will often undergo some change in dimension, but this is usually not critical. However, if dimensions are critical, compensations can be made in the manufacturing process to allow for changes induced by peening.

Stress peening and other specialized peening processes do add to the cost of the peening operation, but can more than offset their cost when severe fatigue problems arise and the size of the spring is limited.

Peening to Resist Stress Corrosion

There are many applications in which the spring is seldom cycled, but is constantly under stress and may be in a corrosive environment. A relief valve is a typical example of such an application. In these situations, stress corrosion cracking may become a problem. This phenomena occurs when surface tensile stresses are exposed to a hostile environment over a period of time and accelerated by temperature. Austenitic stainless steel is particularly susceptible to this attack in the presence of chlorides and fluorides, but many other metals exhibit the same problems in certain environments. The problem will manifest itself as sudden spring failure, even though the spring has limited cycling.

This type of failure occurs because of tensile stresses present at the surface. Shot peening these problem springs produces high magnitude compressive stresses at the surface which negate this problem (fig. 15).



8X UNPEENED 8X SHOT-PEENED

Fig. 15. Type 304 stainless steel U-bend specimens after stress corrosion tests in boiling 42 percent magnesium chloride.

Side Effects of Peening

Shot peening can have an effect on the size and/or mechanical properties of a spring. Because of the residual tensile stresses remaining from the forming operation, which are changed to compressive as a result of the peening operation, the spring may tend to undergo a slight dimensional change. For example, a coil spring will tend to grow slightly. This will mainly occur in thin-section material and small diameter wire. These changes are minor and generally do not represent a problem. However, if the spring has a very critical dimensional tolerance, compensation can be made in the manufacturing process to make allowance for the change in dimension. After shot peening, a minor reduction in spring rate may be noticed. Again, it will be a minor change and usually not of concern, but can be compensated for in the forming of the spring.

Another side effect is an increased tendency of the spring to take a permanent set due to the stresses produced by the shot peening. Consequently, it is common practice to heat springs after the peening process. This is a low-temperature baking process as compared to the higher temperature stress-relief process used after forming or coiling. It is a common practice to bake the springs at 400-450°F for a period of at least 30 min. Temperatures in this range will not have an appreciable effect on the peening stresses, but will greatly affect the set characteristics. This low temperature heating will also tend to counteract any minor dimensional changes which may have taken place as a result of the peening process.

Summary

Springs respond more dramatically to shot peening than do most mechanical parts. Effective shot peening will often allow a spring to be used at 50-70 percent higher stress levels for infinite life than an unpeened spring.

At times, other specialized and individualized peening processes can be used to improve the results achieved by conventional peening practices. These specialized processes may involve higher intensities than normal, extended coverage, multiple processing techniques, etc., and must be tailored to the individual part.

Optimum results can only be obtained by the proper specification as to shot size and intensity, depending upon the individual spring, and by exercising proper control of the process variables of intensity, coverage, and media size and condition.