THE EFFECT OF PEENING SHOT SIZE ON THE PERFORMANCE OF CARBON STEEL SPRINGS[1]

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Summary

The purpose of this investigation was to examine the effect of shot peening on the properties of helical compression springs of various materials and wire sizes, using cast-steel shot sizes between S70 and S550. The springs, made from wire to BS 1408 and BS 2803 materials, were shot peened in a Wheelabrator "Tumblast" machine. With each shot size used, the intensity of peening was determined by the use of an Almen strip. After the springs had been shot peened, they were stress relieved and prestressed before carrying out stress relaxation and fatigue tests.

In the stress relaxation tests, the shot peened springs relaxed more than the unpeened ones—the larger the size of shot used, the greater the relaxation. In the fatigue tests, shot peening was shown to improve the endurance limit of all the springs, the improvement being most marked with the smaller shot sizes. In general, the largest increase was obtained when the shot size was less than a quarter of the wire diameter.

Introduction

Shot peening is now a well established method of improving the fatigue performance of helical compression springs and the effects on different materials have been described in several research reports. The process consists of bombarding the springs with small pieces of rounded shot—usually cast steel or conditioned cut wire—whereby compressive stresses are induced in the surface and immediate sub-surface layers of the wire, which act in opposition to the tensile stresses caused by the loading of the spring. The Spring Research and Manufacturers Association has carried out several investigations into the increase in safe working stress that can be achieved by peening but only in one report[2] has the effect of shot size on the fatigue performance of springs been considered. For that study, three sizes of shot and one spring material were used. In this present investigation the phenomenon has been examined in more

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[1] Presented at the First International Conference on Impact Treatment Processes, Cranfield, United Kingdom, September 5–8, 1983. Reprinted by permission of the *Journal of Mechanical Working Technology*, 1984, vol. 10, pp. 175–185.

[2] Bird, G. C. *An investigation into the effect of shot size in shot peening.* Spring Research Association (SRA) Report, No. 217.

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detail, using a wider size range of shot on a selection of springs materials. In addition, the various parameters involved in the peening operation have been examined, together with measurement of the effect of shot size on several spring parameters.

Spring Designs and Materials

The springs used were made from two different materials: cold-drawn patented carbon-steel wire to BS 1408M Range 2 and hardened and tempered carbon-steel wire to BS 2803 Grade II. The materials were tested in various wire sizes between .064 and .234 in. (1.22 and 5.95 mm.) diameter, springs of each design being shot peened with six sizes of shot, except in the case of the smallest wire diameters, when the largest shot size was not used. The ratio of shot size to wire diameter varied, therefore, from 0.03 to 0.9. This range was larger than that of the previous work, and, in addition, the solid stress[3] was increased to approximately 70 percent of the "as received" tensile strength of the wire, in order to eliminate difficulties encountered previously in fatigue testing some of the springs to failure. Details of the spring designs used are shown in Table 1.

TABLE 1. Spring designs used in investigation.

Material	BS 1408M	Range 2	BS 2803	Grade II
Wire diameter (mm.)	1.63	3.15	4.00	5.74
Mean coil diameter (mm.)	11.4	24.5	30.0	40.1
Spring index	7.0	8.0	7.5	7.0
Total coils	5.5	5.5	5.5	5.5
Active coils	3.5	3.5	3.5	3.5
Free length (mm.) (after pre-stressing)	23.4	48.0	50.0	68.2
Spring rate (N/mm.)	13.5	17.4	27.0	47.4
Solid stress (N/mm^2.)	1517	1200	1100	1100

Shot-peening medium

The medium used for peening the springs was "Wheelabrator" conditioned cast-steel shot, sizes S70, S110, S230, S330, S460, and S550, the number indicating the nominal size (diameter) of the shot in inches × 10^{-4}. (1 inch = 25.4 mm.).

There is no British Standard specification for shot for use in peening, except for a BSCRA specification for steel shot for use in foundry applications. There are, however, SAE specifications for cast steel shot, J444, J827, which cover permitted size range and hardness of shot, respectively.

Shot Peening Plant

The equipment used to shot peen the springs was a Wheelabrator "Tumblast" machine, model WTBOA. The springs to be peened are tumbled on a continuous rubber belt, shot from an overhead storage hopper being fed to the center of a bladed wheel and thrown onto the springs in the cabinet by centrifugal force. A small impellor rotates within the main impellor and carries the shot to an opening in a stationary control cage where it is discharged into the bladed section of the wheel. At this point, the shot is picked up by the inner end of the blades and accelerated in its passage to the periphery of the wheel. The position of the blast stream in relation to the wheel can be altered by rotating the control cage and, for each different size of shot used, needs to be reset in order to be able to obtain the shot pattern in the center of the cabinet.

Once the shot has passed the springs and the holes in the rubber belt, it falls into a trough, from which it is lifted in a bucket elevator, where as it is being raised the finer particles are removed by an extractor fan. As the shot reaches the top of the elevator it passes through an air wash separator where broken and small shot is again removed and discharged into the storage hopper.

The amount of shot thrown on to the springs is controlled by a butterfly valve having four settings: this controls the rate at which coverage is obtained, full coverage taking longer on setting 1 than on setting 4 (full open), although the maximum arc rise is not affected. With the usual setting of No. 3, the flow of S330 shot through the wheel is approximately 350 lb./min. (2.64 kg/s).

The intensity of peening for any given shot size depends upon its velocity, this being governed by the wheel size and speed. The wheel size of the machine was 12 in. (305 mm.) and for the tests the wheel speed was 37.5 Hz, giving a shot velocity of approximately 36 m/s.

Measurement of Peening Intensity

The usual measurement of peening intensity is the Almen arc rise, determined using the Almen strip, holder, and gage[4]. The method is based upon the principle that, if a thin strip of metal is clamped and shot peened on one surface only, the compressive stresses in this side cause the strip to take up a curved shape when it is released, the amount of curvature being related to the effective intensity of the peening. The strips used in the work were Almen A strips. The curvature of the strip is determined by a measurement of the height of the combined longitudinal and transverse arc across standard chords, using the Almen gage.

Calibration Curves

For each shot size used, a calibration curve was produced before peening the springs. A number of Almen strips were placed in the machine, together with a batch of springs to act as ballast, and were peened in the usual manner. At set intervals, two strips were removed and their arc rise measured: by

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[3] Solid stress is the maximum torsional stress induced within the spring when the spring is compressed to the position in which all coils touch each other and no further movement is available from the spring.

[4] Test Strip, Holder and Gage for Shot Peening, SAE Standard J442.

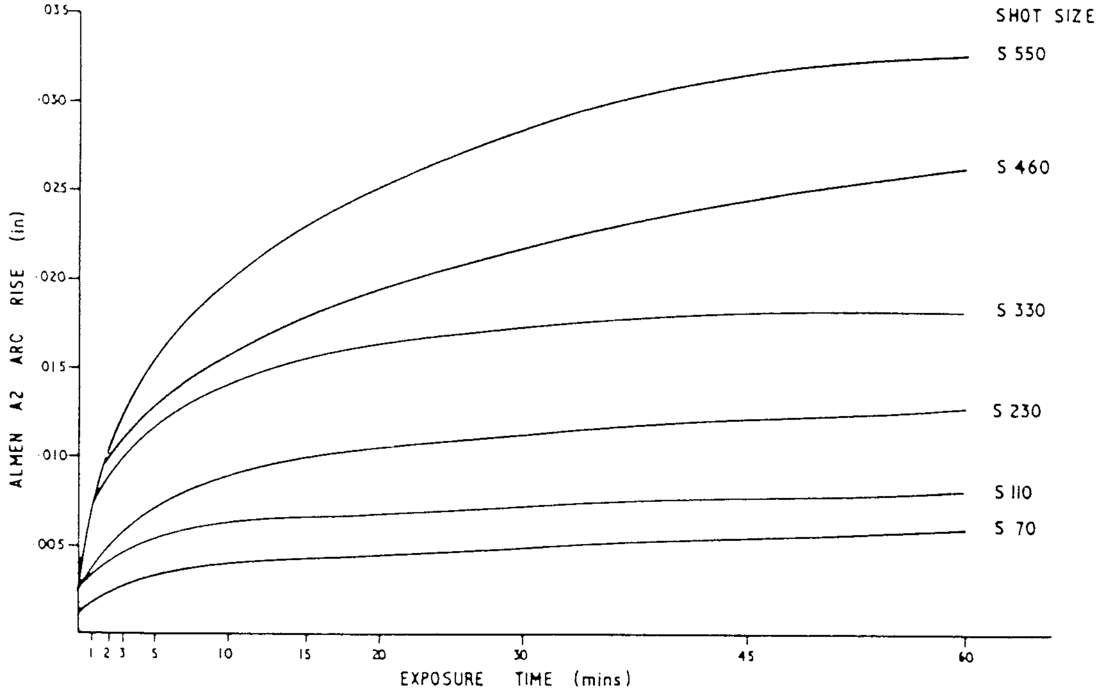

Fig. 1. Calibration curve of shot at the normal wheel speed of 37.5 Hz (1 in. = 25.4 mm.).

this means a curve of Almen arc rise against exposure time could be plotted which enabled the maximum arc rise and the time taken to reach full coverage to be determined for each size of shot.

The calibration curves for the six shot sizes at the normal wheel speed of 37.5 Hz are shown in Figure 1.

Shot Peening Procedure

For each size of shot, the machine was cleaned thoroughly, the new shot introduced, the control cage adjusted to give the shot pattern in the center of the cabinet and the calibration curve produced as described above.

The free length of springs of each design to be shot peened was measured and the batches identified, after which the springs were peened for a period of time that was long enough to give complete coverage, generally 30 min. They were then removed and the free length re-measured, and then given a low-temperature stress-relieving treatment of 437°F (225°C) for 30 min. Finally, the springs were fully pre-stressed before any tests were carried out, the free length being measured before and after pre-stressing.

For each spring design, a batch of springs was used as a control group—not being shot peened but being subjected to all the tests.

Stress Relaxation Tests

In order to assess the effect of the size of shot on the relaxation of the springs at elevated temperatures, springs from two different materials which had been peened with all six sizes of shot were subjected to stress relaxation tests together with batches of similar unpeened springs.

TABLE 2. Results of tests to determine relaxation in peened springs.

Material	Wire diameter ((mm.)	Stress levels (N/mm².)	Temp. °F(°C)	Time (hr.)
BS 1408M Range 2	3.15	500,700,900	257(125)	72
BS 2803 Grade II	4.0	300,500,700,900	302(150)	72

The springs were load tested, clamped on Monel bolts at various stress levels, and held in an air-circulating furnace for 72 hr. After being removed from the furnace, they were load tested again to determine the loss in load—and hence the relaxation—that had occurred. Details of the tests carried out are given in Table 2 and the results obtained are shown in Figure 2 and 3.

Fatigue Tests

Springs of six different designs which had been peened with the various sizes of shot were fatigue tested on a forced motion fatigue testing machine to produce a series of *S/N* curves, all with an initial stress of 100 N/mm². In order to assess the improvement in fatigue properties, a batch of unpeened springs of each design was first tested to produce a control curve.

Discussion of Results

1. Calibration curves

The calibration curves for the shot peening plant shown in Figure 1 indicate that the larger the shot, the greater the arc rise produced. For peening peri-

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ods of 1 hr. a linear relationship is obtained between the measured arc rise and the shot size.

2. Free-length variation

Tables 3–5 show the average free-length of three of the spring designs used after shot peening, after the (low-temperature heat-treatment) LTHT following peening and after pre-stressing, together with the free-length after prestressing of the unpeened springs. As can be seen in the tables, the size of shot does not have any noticeable effect on the free-length value after peening, stress relieving or pre-stressing. This confirms other recent work carried out by SRAMA which showed that, for springs manufactured from material to BS 5216 and given a stress-relieving heat-treatment between 392°F (200°C) and 482°F (250°C) after shot peening, the solid stress after pre-stressing was the same as that of similar unpeened springs.

TABLE 3. Average free-length of springs from 1.63 mm. diameter wire to BS 1408M Range 2 after peening.

	Unpeened	**Shot size**					
Free-length (mm.)	**springs**	S70	S110	S230	S330	S460	S550
After shot peening	—	30.7	30.7	30.6	30.6	30.6	30.6
After shot peening and LTHT	—	30.8	30.8	30.7	30.6	30.6	30.6
After pre-stressing	23.4	23.4	23.4	23.4	23.5	23.4	23.4

TABLE 4. Average free-length of springs from 3.15 mm. diameter wire to BS 1408M Range 2 after peening.

	Unpeened	**Shot size**					
Free-length (mm.)	**springs**	S70	S110	S230	S330	S460	S550
After shot peening	—	51.3	51.2	51.6	51.1	51.4	51.2
After shot peening and LTHT	—	51.3	51.2	51.5	51.3	51.4	51.2
After pre-stressing	48.4	47.8	47.8	47.6	47.5	48.3	48.0

TABLE 5. Average free-length of springs from 5.75 mm. diameter wire to BS 2803 Grade II after peening.

	Unpeened	**Shot size**					
Free-length (mm.)	**springs**	S70	S110	S230	S330	S460	S550
After shot peening	—	73.0	72.7	72.9	72.8	72.8	72.9
After shot peening and LTHT	—	73.0	72.7	72.8	72.8	72.8	72.8
After pre-stressing	68.5	68.0	68.3	68.2	68.3	68.0	68.1

3. Stress relaxation results

Recent work carried out by SRAMA on the stress relaxation properties of springs from high-tensile carbon-steel wires[5] has shown that when unpeened

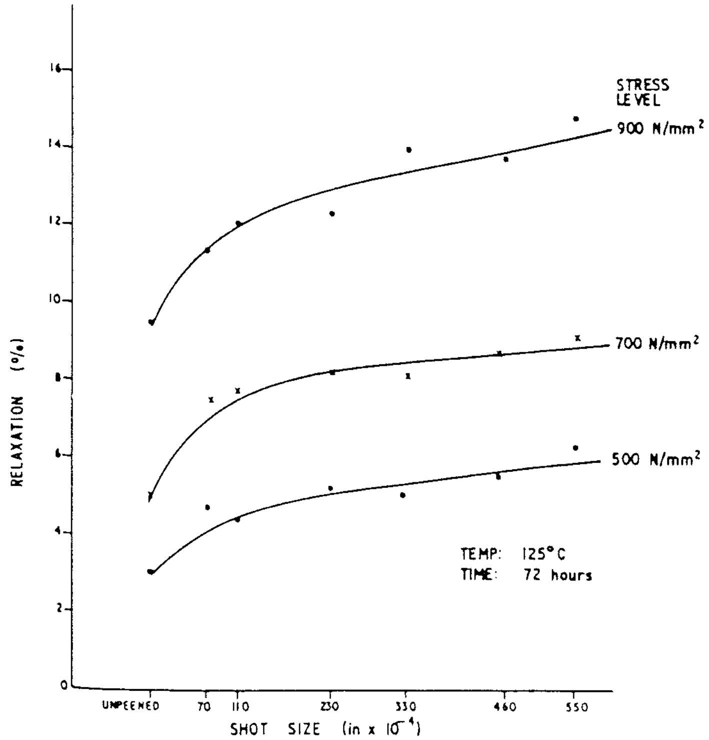

Fig. 2. Stress relaxation tests of 3.15 mm. diameter BS 1408 M Range 2 springs.

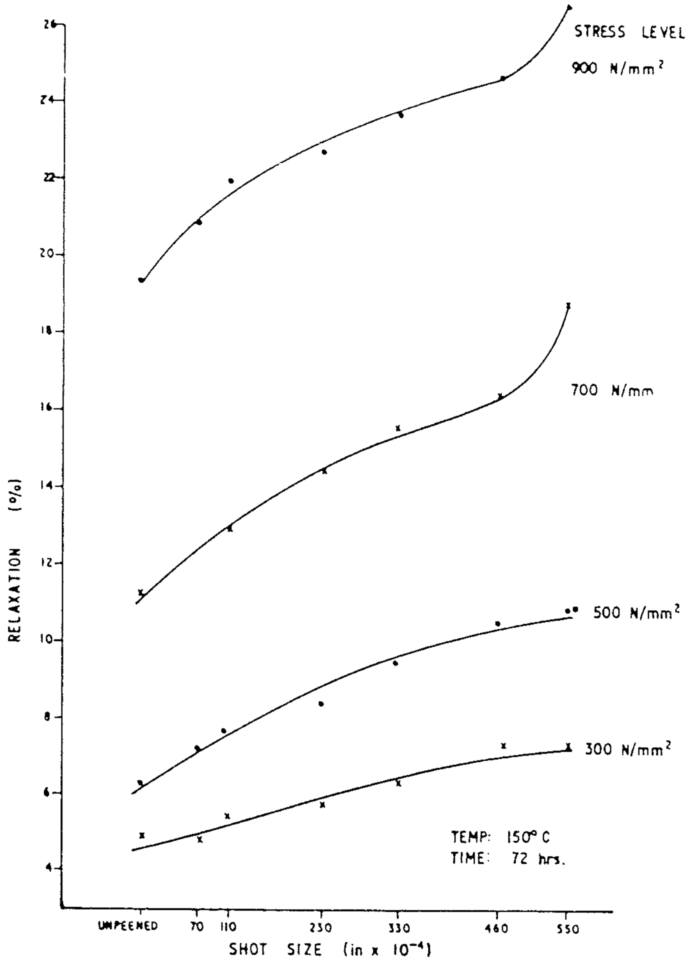

Fig. 3. Stress relaxation tests of 4.00 mm. diameter BS 2803 springs.

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[5] Gray, S. D. and G. B. Graves, The properties of BS 1408 MRI and R2 wires and springs, SRA Report No. 246.

and shot-peened springs have been held at the same stress and temperature, the shot-peened springs exhibit greater relaxation. The data so far produced have only related to springs peened with one size of shot. The stress relaxation tests on springs peened with different sizes of shot cover two different materials and temperatures. The results are shown in Figures 2 and 3, in which the effect of peening the springs with larger shot on the stress relaxation at a particular stress level can clearly be seen. In both cases the shotpeened springs relaxed more than similar, unpeened ones: the larger the shot—and hence the greater the amount of residual stress induced by the peening—the greater was the relaxation. It was also noticeable that, for similar springs, the increase in relaxation with increasing shot-size was more marked at the higher stress levels.

In interpreting the above results, the point can be made that the relaxation of a spring under a combination of applied stress and heat with time is nothing more than mechanical creep, but at diminishing rather than constant stress. When a spring is shot peened a large number of dislocations and vacancies are introduced into the structure of the material in the outer layers. Under the applied stress and heat these dislocations and vacancies move within the structure of the material: this then manifests itself as overall relaxation within the spring. The maximum compressive stress induced in shot peening is not a function of shot size, but the depth of affected material certainly increases with increased shot sizes. As a result, a greater volume of material is affected, therefore larger numbers of dislocations and vacancies are induced, and as a result the overall relaxation levels are increased.

4. *Fatigue properties*

The effect of shot size on the fatigue properties of the springs, as summarized in Figure 4, is probably the most interesting feature of this work.

From the result of the fatigue tests on the cold-drawn carbon-steel wire to BS 1408M Range 2, it can be seen that for both wire sizes the effect of increasing the shot size is to reduce the fatigue limit. From the *S/N* curves it was also established that the fatigue strength at working stresses above the fatigue limit was reduced. In addition, the effect of the largest shot sizes used—S460 and S550—was to reduce the fatigue performance at particular stress levels below that of the unpeened springs.

The springs made from oil-tempered .226 in. (5.74 mm.) diameter wire to BS 2803 also showed a similar maximum increase in the fatigue limit. The maximum increase in the fatigue limit, 32 percent, was similar to that of the other two carbon steel wires, although the wire diameter was larger, and the optimum shot size ratio was again about 0.1.

To summarize the fatigue data, the percentage increase in the fatigue limit was calculated for each shot size/wire diameter ratio. The curves for the six carbon-steel materials tested in this and previous work[6] are plotted in Figure 4. The data for the 0.12 in. (3.15 mm.) and 0.064 in. (1.63 mm.) diameter wires to BS 1408M Range 2 and the 0.226 in. (5.74 mm.) diameter wire to BS 2803 give similar curves to

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[6] Bird, Spring Research Report No. 217.

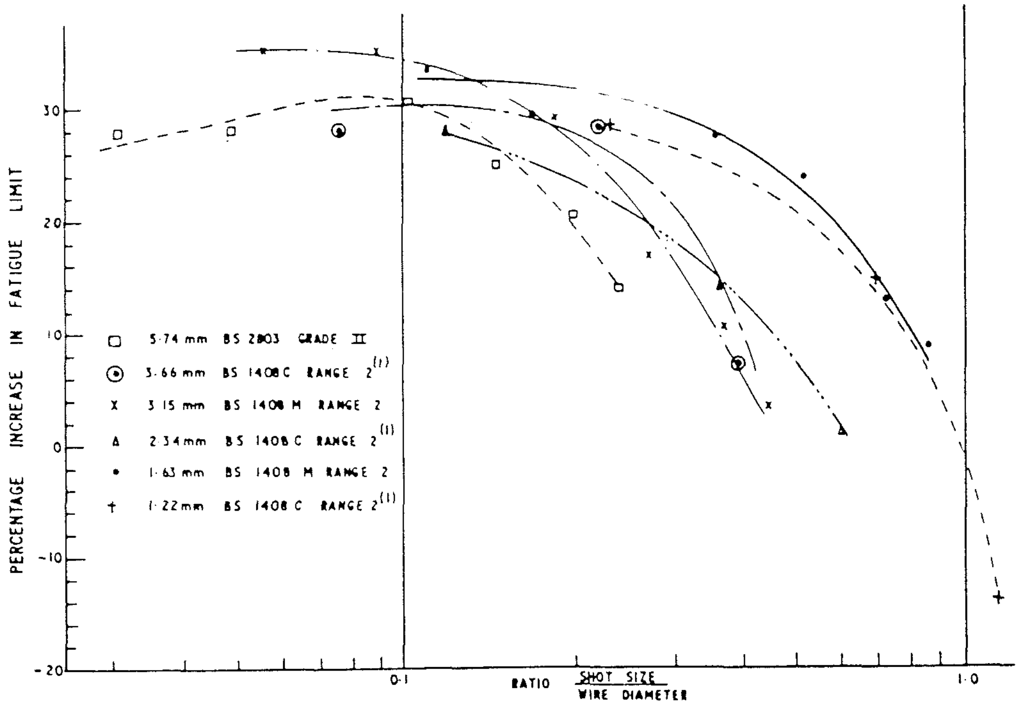

Fig. 4. Summary of fatigue data for carbon steel springs.

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that previously obtained for springs from BS 1408C Range 2. Except where the fatigue limit was affected by the solid stress of the springs, the maximum increase for all these materials was between 30 percent and 35 percent.

From the summary of the fatigue data in Figure 4 it is apparent that the greatest increase in fatigue performance is obtained when the shot size used is less than about 10 percent of the wire diameter, for carbon-steel springs.

It can also be seen that for the smaller wire diameters the same increase in fatigue properties can be obtained with a larger shot-size/wire-diameter ratio. Thus with a wire diameter of 0.04–0.06 in. (1–1.5 mm.) a shot size ratio of 0.5 will still give an increase of above 20 percent, whereas the same shot-size ratio of 0.12 or 0.16 (3 or 4 mm.) diameter wire would give very little increase in fatigue performance. This is very important in practice because it means that a single shot size can be used which will give a good increase in fatigue properties over a wide range of wire sizes.

It should be borne in mind, however, that all the wires used had little or no decarburization. On springs which have been hardened and tempered after coiling, therefore, larger shot may be nceessary to penetrate any surface decarburization present and induce residual stresses in the body of the material.

Conclusions

a. As might be anticipated, the larger the shot used in peening, the larger the Almen arc rise obtained.

b. With suitable low-temperature heat-treatment after shot peening, the solid stress after pre-stressing is the same for both peened and unpeened springs.

c. At elevated temperatures, shot-peened springs relax more than unpeened springs and the larger the shot size used, the greater the amount of relaxation.

d. All springs peened with S550 shot, which gave the largest Almen arc rise, exhibited the poorest fatigue performance of the shot-peened springs.

e. The largest improvement in fatigue performance was obtained when the shot size was approximately one-tenth of the wire diameter, for carbon-steel wire springs.

f. The maximum improvement in fatigue limit that could be obtained with carbon-steel springs was approximately 30 percent.

Practical Applications

When considering the practical case of a spring manufacturer using a shot peening plant where a range of materials and wire sizes need to be handled, it is obvious that the shot in the plant cannot be changed to give the optimum performance for every batch of springs. It is necessary, therefore, to compromise and, depending upon the number of machines available, to choose a shot size or sizes that will be suitable for all the springs to be peened in the particular machine. The information given in this report can be used as a guide to shot selection, other points which need to be taken into consideration being as follows:

a. The spring design may limit the improvement in fatigue properties that can be achieved. This was indicated in previous work[7] where the maximum increase in the fatigue limit was governed by the solid stress of the spring as well as the size of shot.

b. The result of this work indicate that although the maximum increase in fatigue performance for carbon-steel wire is obtained with a shot size about 10 percent of the wire diameter, for wire sizes about 0.04–0.06 in. (1–1.5 mm.) diameter a marked improvement is still obtained when the shot is half the size of the wire. Thus, if only one plant is available, a single shot size can be chosen which will still give an effective increase in fatigue performance over a wide range of wire sizes.

c. In order to obtain a beneficial effect from shot peening the shot needs to strike the inside surface of the wire, so the use of a smaller shot is necessary where springs have a low index or little space between the coils.

d. When designing springs for fatigue applications, it should be borne in mind that the improvement in fatigue life produced by shot peening decreases as the initial stress on the spring is increased. The fatigue tests in this report have all been carried out at an initial stress of 100 N/mm^2 so the percentage improvements in fatigue limit of springs working with an initial stress greater than this will be smaller than those quoted.

e. The data produced in this report using the plant of the Spring Research and Manufacturers' Association gives an indication of the improvement that can be achieved. It is important to realize that this can only be achieved and maintained if the plant is properly supervised. The major variables affecting the process are the shot—the average size of which will gradually reduce—and the position of the blast stream, which latter should be checked regularly to see that the springs are being peened rather than the walls of the cabinet. The easiest method of checking these parameters is by the use of Almen strips placed at various positions in the cabinets. The arc rise can then be checked to see that an even shot pattern is being maintained and that the correct intensity is being achieved.

f. Where there is more than one peening plant in operation, the shot in each should be chosen such that when the largest shot has broken down to an inefficient size it can be used in the next smallest machine.

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[7] Bird, SRA Report No. 217.