

Fatigue strength of shot peened helical tension and compression steel springs

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FATIGUE STRENGTH OF SHOT PEENED HELICAL TENSION AND COMPRESSION STEEL SPRINGS

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FATIGUE STRENGTH OF SHOT PEENED HELICAL TENSION AND COMPRESSION STEEL SPRINGS

1. INTRODUCTION

Springs can fail for many different reasons such as inadequate quality in design or during the manufacturing process, or because of unexpected loading leading to departure from design whilst in use. Repeated or varying loading can lead to fatigue fracture as well as wear, fretting and corrosion of springs. Modifications to the design of the spring assembly may reduce the applied stress on the spring therefore increasing its fatigue life. One such change, for example, involves replacing a single spring with a nest of springs to lower the overall stress range (Derivation 1 and ESDU 82012^{*}) or applying a post manufacturing treatment, such as shot peening (ESDU 19004[†]) to the spring to improve its fatigue strength.

An outline of steel spring material selection and design, and a general overview of post-manufacturing treatments that could be applied to springs, are given in Section 3. In particular, this Data Item considers the benefits of using shot peening to improve the fatigue properties of helical compression and tension steel springs. Shot peening improves the fatigue durability of a metal by cold working to alter the physical properties at the surface and by inducing residual compressive stress. These compressive stresses resist the material being stressed in tension meaning that the load carrying capability of the spring is improved.

In this Item, most of the data showing the effect of shot peening on the fatigue strength of steel springs are from tests carried out on spring steel specimens, rather than on springs themselves. In most instances, the curves drawn through the endurance data in Section 7.2 have been derived using ESDUpac A9724, a program that accompanies ESDU 97024[‡]. Note that the fatigue data in Figures 5 to 13 are from either single tests or an average of multiple test results and will be subject to scatter, (see ESDU 97024 for further details).

Section 4 discusses the influence of shot peening on the residual stress distribution at the surface of springs and spring steels. The influence of variables such as shot size, environment and stress ratio on the fatigue properties of non shot peened and shot peened spring steels are given in Section 5.

2. NOTATION

Both SI and British units are quoted but any coherent system may be used.

A or C	Almen intensity, see ESDU 19004	m	in
a	depth of slit	m	in
c	width of slit	m	in
N _f	number of cycles to failure	cycles	cycles
R	stress ratio		
S _a	stress amplitude	N/m ²	lbf/in ²

^{*} ESDU 82012, 'Nested helical compression springs of round wire (To be used in conjunction with ESDU 82008)'.
[†] ESDU 19004, 'Guide to the effect of shot peening on fatigue strength'.
[‡] ESDU 97024, 'Derivation of endurance curves from fatigue test data, including run-outs'.

3. SPRING MATERIALS AND OVERVIEW OF SURFACE TREATMENTS

Springs are designed to withstand fatigue loading by using materials with a high tensile strength to withstand large stresses during loading. A high hardness value is important, from the point of view of wear, however if the hardness value is too high it may cause fatigue fracture due to notch sensitivity linked to small defects in the material. As well as material selection, the physical dimensions of the spring (such as spring index), its anticipated durability, the service requirements and the working environment are all details of the design process that should be evaluated against the cost of manufacture. Introducing compressive residual stresses at the surface of steel springs, induced by carburizing, nitriding or shot peening, is a proven way of reducing the mean stress in the spring and improving the fatigue life.

3.1 Material Selection

Springs made from a Cr-V or a Cr-Si grade steel are useful for a wide variety of applications because of the availability of these steels at a relatively low cost. High strength spring steels tend to be alloyed to improve durability and are designed to undergo thermal treatments to raise the yield strength and fatigue resistance whilst maintaining material properties such as toughness and impact resistance. Other characteristics such as resistance to relaxation under load, the tendency to surface decarburisation and hardenability of the steel are also of interest to the spring designer (Derivation 5).

Cr-V steels are high-strength steels which have a fine grain structure containing vanadium carbides that limit further grain growth. In addition, these steels have good resistance to surface decarburisation (Derivation 5).

Cr-Si steels are also high-strength steels and are comparatively cheaper than Cr-V steels. Silicon is used to enhance the steel's resistance to tempering of the martensite structure and can limit the relaxation of load (sag resistance) due to the refinement of the tempered carbides (Derivation 5).

Springs made from Ni-Cr-Mo steel have high toughness and can be heat treated to high hardness levels whilst maintaining significant levels of ductility. Ni-Cr-Mo steels also have good hardenability even though they have lower carbon content and their fatigue resistance is less than for Cr-V and Cr-Si steels because of their lower elastic limit.

If the working environment is corrosive, then springs may be made using a stainless steel such as a 17-7PH steel or similar. For springs operating at high temperatures, then a 301 or a 302 stainless steel may be used, however the design stresses for such springs should be lower particularly when they are used for high temperature applications (Derivation 21).

3.2 Post Manufacturing Treatments

Springs tend to be designed so that the greatest working stress at the maximum working deflection does not exceed about 40-45 per cent of its minimum yield strength for both tension and compression springs, and 75 per cent of the shear yield strength for torsion springs. The minimum tensile strength is, however, different for different wire diameters and higher tensile strengths are indicated for smaller wire diameters (Derivation 21).

Fatigue strength is influenced by the behaviour of the surface of the material. Mechanical surface treatments introduce compressive residual stresses near to the surface that help to increase the fatigue strength of the component (Derivation 19).

3.2.1 Shot peening process

Shot peening is a mechanical process for applying cold work to the surface of a metal or component to improve the fatigue strength and stress corrosion cracking resistance (Derivation 7). During shot peening, a stream of hard particles is projected at high velocity at the surface to generate compressive residual stresses and work hardening at and just below the surface layer (Derivation 16). Shot peening will increase the hardness and the residual stress field in a component whilst mechanically cleaning and improving the uniformity of the surface. Shot peened steels show no decrease in fatigue strength as hardness of the metal is increased (by changing tempering temperature), as seen for non shot peened steels (Derivation 18). Shot peened springs have a greater fatigue endurance and improved corrosion and wear resistance (Derivation 4). Table 7.1 summarises the parameters involved in the shot peening process and lists the advantages of using this process (Derivation 4). To achieve the highest possible fatigue strength, these parameters must be optimised and monitored. The types of shot used and the control of shot peening intensity using an Almen strip are discussed in ESDU 19004.

Imparting residual compressive stresses by means of cold work in the surface layers improves the fatigue strength of springs but can be a complex process to apply with many input variables. To obtain the maximum fatigue strength, the designer must consider the material response to residual stresses, cold work, surface roughness, micro-cracks and micro-structure changes. An overview of numerical methods that consider both favourable and detrimental aspects of these responses during shot peening is reviewed elsewhere (Derivation 17).

3.2.2 Other processes

- Dry honing is a method of surface processing using abrasive grains sprayed directly on to the surface using compressed air to achieve a smooth surface and a peening effect (Derivation 16).
- Liquid honing is a process of cleaning the surface by spraying it with water containing minute polishing agents, sometimes with appropriate corrosion retardants, while improving the fatigue strength like shot peening – this process can be applied when dry shot peening would cause too much distortion (Derivation 16).
- Hot peening is like shot peening but is carried out at temperatures between 150 and 350 °C (302 and 662 °F) for spring steels to produce an aging effect and enhanced compressive residual stresses especially in hard steels (Derivation 16).
- Presetting is a method to increase stress relaxation resistance and durability by applying a load, below the yield point of the material, to a spring before it is used. This load should exceed the maximum value expected during service thus generating a certain degree of permanent distortion (Derivation 16). This process is either carried out at room temperatures, and is known as cold setting, or is carried out at a low annealing temperature, known as hot setting (Derivation 16). Presetting is not recommended for springs used for critical applications (Derivation 21).

4. RESIDUAL STRESS DISTRIBUTION

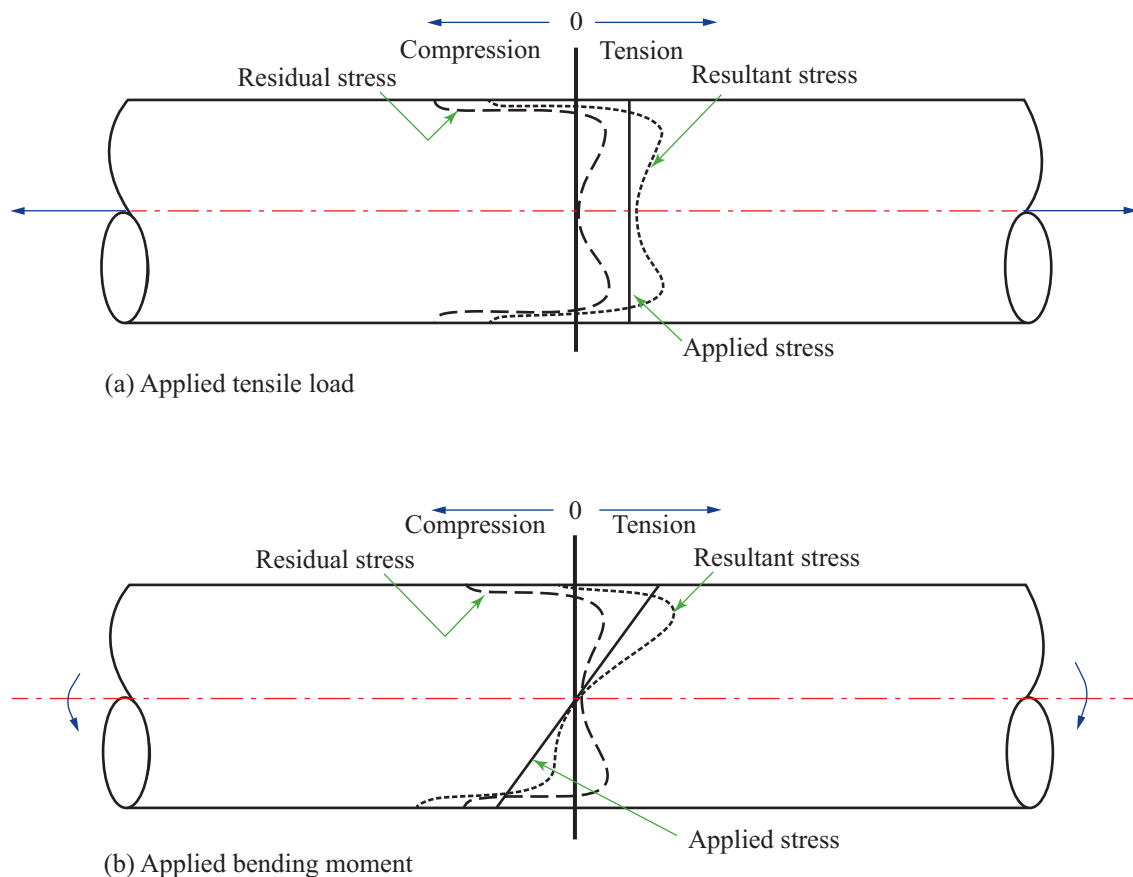
The amount of residual stress induced at the surface of the shot-peened metal depends mainly on material properties such as the tensile strength or the hardness. Shot peening parameters, such as the velocity of the shot, the degree of coverage, and the diameter of the shot only slightly affect the amount of residual compressive stresses at the surface.

Fatigue failures often initiate at the surface of a component and propagate under cyclic loading until failure occurs. For fatigue cracks to initiate, the surface must be under tensile stress. If there is already compressive stress in the surface region before loading, the resultant tensile stress in the surface will be reduced and any cracks will be less likely to initiate and propagate.

Residual stresses are also created in tension and compression springs during the presetting process because of plastic yielding in the spring wire, followed by unloading of the spring. If the presetting load is in same direction as the service loading, the residual stress fields after yielding will act in a beneficial direction therefore increasing the operating load without inducing further plastic yielding (Derivation 6).

The improvement of fatigue strength in a component after shot peening is governed by the magnitude and depth of the beneficial residual compressive stresses at and below the surface. Sketch 4.1 shows how, in principle, these residual stresses reduce the tensile stress in a component subject to axial loading or bending. It is also important that the compressive stresses remain throughout the lifetime of the component to enhance the improvement in fatigue strength. Any heat treatments after shot peening may cause stress relaxation that would reduce any benefits obtained from the shot peening process in the first place.

During shot peening, there is no simple relationship between the Almen intensity (see ESDU 19004 for further details) and the maximum compressive stress produced at the surface. However, using larger shot (which produces higher Almen intensities) tends to produce greater compressive stresses in harder materials.



Sketch 4.1 Interaction of residual and applied stresses (from ESDU 19004)

4.1 Effect of Surface Decarburisation

Surface decarburisation can happen during the heat treatment of most spring steels and the depth of the decarburised layer can be controlled. Figure 1 shows a decarburised layer depth designed to be only 0.1 to 0.2 mm (0.004 to 0.008 in) below the surface. However, it can be up to 0.5 mm (0.0196 in) below the surface (Derivation 14 and 19).

Shot peening introduces a plastic deformation zone that can reduce the detrimental effects of decarburisation below the surface. In this plastic deformation zone, the compressive residual stresses at the surface and the amount of work hardening increase, both of which improve the resistance to fatigue crack initiation and propagation.

Figure 1 also shows the relatively flat residual stress distribution below the surface of shot peened 51SiCr7 steels subjected to four different heat treatments that give decarburisation depths of between 0.15 and 5 mm (0.006 and 0.196 in) (Derivation 14 and 19). The amount of compressive stress is similar in all the decarburised specimens, and note that this compressive stress is less than for the reference specimen with no decarburisation. Figure 2 presents a similar residual stress profile for shot peened 55Cr3 spring steels decarburised for 20 and 90 minutes followed by shot peening (Derivation 4). The residual compressive stresses below the surface are slightly reduced with increasing decarburisation time.

4.2 Effect of Pre-stress During Shot Peening

Figure 3 shows the beneficial effects of applying a pre-stress of up to 75 per cent of the yield strength during shot peening on the compressive residual stresses below the surface of a 55SiMnVB spring steel (Derivation 3). Figure 4 shows that a pre-stress of 1250 MN/m^2 ($181.3 \times 10^3 \text{ lbf/in}^2$) applied using a four point bending system during shot peening increases the amount of compressive residual stress below the surface of a SUP9 spring steel that contained a semi-circular slit (Derivation 20).

4.3 Effect of Shot Peening Intensity and Percentage Coverage

It was reported that a greater shot peening intensity increases the maximum compressive residual stress below the surface of the metal, whilst also increasing the width and the depth of the compressive residual stresses zone for an AISI 4340 steel (Derivation 10). However, it was noted that the stresses at the surface are independent of shot peening intensity as the surface stresses are more related to the mechanical properties and surface condition of the metal, rather than the shot peening conditions. In the high cycle regime cracks initiated in the compressive stress field. However, in the low-cycle regime, the cracks originated at the surface (Derivation 10).

There was no significant increase in maximum compressive residual stress or the size of the residual stress zone below the surface by raising the percentage coverage to more than 20 per cent (Derivation 9).

4.4 Relaxation

In Figures 5a to 5d the relaxation of compressive residual stresses is shown for non heat treated and decarburised specimens made from shot peened 51SiCr7 spring steel wire which was fatigued at two different stress amplitudes (Derivations 14 and 19). In Figure 5a to 5d, Site 1 on the specimen is originally in compression during the first quarter of the stress-strain cycle, and Site 2 is in tension. The corresponding relaxation at Site 2 is more gradual than for Site 1 however they tend to reach similar stationary levels after about only 1 per cent of the lifetime (1000 to 10 000 cycles) beyond which no further relaxation happens.

The recovery of compressive stresses occurs faster at higher stress amplitudes and can be as much as half the value of the beneficial compressive residual stress produced after shot peening (Derivations 10, 14 and 19). After recovery, fatigue cracks are mostly observed at the surface, but for one specimen without any decarburisation a fatigue crack was observed below the surface on an inclusion after low stress amplitude loading at 10^7 cycles (Derivations 14 and 19).

5. FATIGUE OF SPRING STEELS

Figure 6 shows the fatigue strength of a Cr-V spring steel and Figure 7 shows the fatigue strength of Cr-Si spring steel. Cr-V spring steels do not deteriorate, in terms of fatigue strength, in the high cycle regime (10^6 and 10^9 cycles) compared to Cr-Si spring steel which does. For both the Cr-V and Cr-Si spring steels, it was observed that fatigue cracks originated below the surface on internal defects (inclusions) when the number of cycles was beyond 10^7 , and at lower number of cycles the fatigue cracks initiated at the surface (Derivation 8).

On Table 7.2 a higher hardness temper improves the fatigue limit of the Cr V and Cr Si spring steels, but not that of Ni-Cr-Mo spring steel, during rotating bending fatigue tests (Derivation 5). Table 7.3 shows an improvement in fatigue strength of between 41 and 81 percent for several spring steel wires after shot peening (Derivation 2). Shot peening also improves surface quality by removing unwanted particles and improving topography, and it also reduces any surface stress concentrations in the spring wire. Shot peening was reported to further improve fatigue strength by 20 per cent for previously polished specimens and up to 65 per cent for surface decarburised specimens, and produce nearly a 100 per cent improvement for surface oxidised specimens (Derivation 4).

5.1 Stress Ratio

Figures 8a to 8h show the effect of increasing the stress ratio, R , between 0.1 and 0.7 on 1 and 4 mm (0.04 and 0.157 in) wire diameter non shot peened and shot peened springs made from cold drawn piano wire (SWP-A) steel and 1 and 3.5 mm (0.04 and 1.38 in) wire diameter oil tempered Cr-Si (SWOSC-V) steel springs (Derivation 23).

5.2 Shot Peening Intensity

For an AISI 4340 spring steel, Figure 9 shows that though there was an increase in fatigue resistance when the intensity of shot peening intensity increased up to about 0.063A, beyond this intensity there is no further benefit to fatigue resistance (Derivation 10). During fatigue testing in the low cycle regime fatigue cracks originated at the surface but in the high cycle regime it was noted that cracks initiated below the surface because of the compressive residual stress field at the surface. Selecting the most beneficial intensity of shot peening to increase in fatigue strength would reduce the amount of relaxation of compressive stress, improve the surface condition and create a compressive residual stress field to limit the initiation of cracks below the surface (Derivation 10).

5.3 Percentage Coverage

The percentage coverage during shot peening is related to the fraction of the area impacted by the shot (dimple diameter and total impacts) and to the time used to saturate Almen strip. Figure 10 shows that the full benefit from shot peening could be realised at less than 100 per cent coverage and that an excessive coverage of 300 per cent would actually reduce the fatigue lives and endurance limit (Derivation 9). A reduction in percentage coverage means shorter shot peening times and using a larger shot size would give deeper compression and residual cold work without any loss of fatigue performance (Derivation 9).

5.4 Decarburisation

The fatigue tests for decarburised 51SiCr7 spring steel specimens are given in Figure 11. The fatigue limit of the reference specimen that has not been decarburised is greater than that for the decarburised specimens. The improvement in fatigue strength after shot peening was larger for the decarburised specimens (Derivation 14 and 19).

5.5 Pre-stress During Shot Peening

Figure 12 shows that when a pre-stress of up to 980 MN/m^2 ($142.1 \times 10^3 \text{ lbf/in}^2$) was applied during the shot peening process, the fatigue life increased by up to 70 per cent (Derivation 3). This steel had a decarburised layer of about 0.13 to 0.16 mm (0.005 to 0.006 in) depth and it was noted that fatigue cracks initiated at the surface however, the propagation of these cracks was delayed by the large compressive residual stresses formed during shot peening.

In Figures 13a to 13d, even though the quenched and tempered SUP9 spring steel sample contained a semi-circular slit the beneficial effects of applying a pre-stress during shot peening is still evident. As expected, the fatigue limit improves when a pre-stress is applied during shot peening compared to no pre-stress during shot peening. Additionally, all the samples with a pre-stress applied during shot peening fractured elsewhere than at the semi-circular slit. The samples containing a semi-circular slit with a pre-stress applied during shot peening had fatigue limits equivalent to those of shot peened smooth samples due to other compressive residual stress forming at the slit caused by a tensile overload (Derivation 20).

5.6 Effect of Corrosion

Table 7.4 shows the effect of a corrosive environment has on reducing the fatigue strength of a hardened and tempered samples of Cr-Si spring steel (50HS). However, when the corroded spring steel specimens are shot peened, the fatigue strength of the samples was reported to have improved up to values close to those of those of un corroded samples (Derivation 12).

Shot peening also increases the corrosion fatigue strength of torsional fatigue tested SUP7 (480 HV hardness) steel specimens (Derivation 15), however the corrosive environment did increase the number of microcracks just below the surface. For high strength spring steel specimens (SUP9 and SUP 10M) fatigue tested in a 3 per cent NaCl aqueous solution, the beneficial effects of shot peening on improving fatigue strength are less obvious in the high cycle regime when corrosion and corrosion pits initiate easily, even when there are compressive residual stresses at the surface (Derivation 11).

5.7 Shot Peening Temperature

Shot peening is normally carried out at room temperature, however Table 7.5 shows that if it is done at a higher temperature then the fatigue life of SAE 5160 spring steel will increase. Raising the shot peening temperature too much increases the amount of surface roughness and reduces residual stress, however at an optimum temperature for steel samples (200°C (392°F)) any strain hardening introduced by shot peening locally increases yield strength making it harder for fatigue cracks to nucleate (Derivation 13).

5.8 Effect of Dual Shot Peening

A dual shot peening process is one where the single shot peening process is repeated to allow for a redistribution and relaxation of residual stresses in between the processes. For example, a quenched and tempered AISI 9254 steel spring subject to a dual shot peening process showed a greater increase in fatigue life compared to samples that had only been shot peened once because of the greater amount of compressive residual stress just below the surface where fatigue damage initiates (Derivation 22).

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7. FIGURES AND TABLES

7.1 Tables

TABLE 7.1 Effect of shot peening on component properties (modified from Derivation 4)

Shot peening parameters (see also ESDU 19004):	
Setting parameters	Velocity of shot Impact angle Mass throughput Operating time Degree of surface coverage
Shot design	Particle shape, hardness, mass, size, material, size distribution Wear condition
Benefits of shot peening process:	
Surface layer modifications	Hardness increase Creating residual stress layer Removal of material Surface topography Dimensional, positional and form deviations
General material property modifications	Fatigue strength Corrosion resistance Wear resistance Surface diffusion behaviour (e.g. hydrogen absorption) Improvement and uniform surface conditions Form changes

TABLE 7.2 Fatigue strength of some spring steels with no shot peening (Derivation 5)

Steel	Temper [*]	Mean fatigue limit for life of 2.8×10^6 cycles, $\text{MN/m}^2 (\times 10^3 \text{ lbf/in}^2)$	Standard deviation
50CrV4	H	752 (109.1)	14.9
	L	698 (101.2)	8.4
60SiCr8	H	746 (108.2)	18.4
	L	712 (103.3)	14.9
39NiCrMo3	H	677 (98.2)	10.5
	L	678 (98.3)	7.6

* H – higher-hardness temper, hardness 44 to 46 HRC (tempered at 440 to 500 °C (824 to 932 °F for 1 hour).

L – lower-hardness temper, hardness of 39 to 41 HRC (tempered 530 to 575 °C (986 to 1067 °F for 1 hour).

All the specimens 6 mm (0.24 in) minimum diameter, hourglass shaped specimens, polished surface finish of $R_A = 0.02$ to 0.05 μm (0.79 to 1.97×10^{-6} in) on the shaped length.

TABLE 7.3 Fatigue strength of some helical spring wires (Derivation 2)

Spring wire and diameter	Test duration, $\times 10^6$ cycles	Fatigue strength		Percentage improvement
		Non shot peened $\text{MN/m}^2 (\times 10^3 \text{ lbf/in}^2)$	Shot peened $\text{MN/m}^2 (\times 10^3 \text{ lbf/in}^2)$	
Piano wire, 1 mm (0.039 in)	0.4	827 (120)	1310 (190)	58
Oil tempered, 5.3 mm (0.2 in)	10	586 (85)	827 (120)	41
Hot coiled 1095, 19 mm (0.75 in)	2	414 (60)	621 (90)	50
Stainless steel 18-8	10	552 (80)	827 (120)	50
S-816	10	379 (55)	689 (100)	81

TABLE 7.4 Ultimate tensile strength and fatigue strength of Cr-Si (50HS) spring steel (Derivation 12)

Test surface condition	Ultimate tensile strength, $\text{MN/m}^2 (10^3 \text{ lbf/in}^2)$	Fatigue strength, 10^7 cycles, $\text{MN/m}^2 (10^3 \text{ lbf/in}^2)$
Non shot peened	1637 (237.4)	780 (113.1)
Shot peened	1653 (239.7)	860 (124.7)
Non shot peened and corroded	1648 (239)	640 (92.8)
Shot peened and corroded	1623 (235.4)	780 (113.1)

Rotating beam fatigue test $R = -1$ 100 Hz frequency

Shot peening variables: 0.6 mm (0.024 in) diameter shots 700 HV hardness 0.45 mmA intensity

Corrosive solution containing ammonium sulphate $(\text{NH}_4)\text{SO}_4$ and sodium chloride and concentrated sulphuric acid for up to four weeks

TABLE 7.5 Fatigue life of shot peened SAE 5160 spring steel samples at different temperatures (Derivation 13)

Shot temperature, $^{\circ}\text{C} (^{\circ}\text{F})$	Hardness after tempering, HV	Mean life, cycles	Standard deviation
—	491	8396	3253
25 (77)	528	155 038	2070
25 (77)	491	46 154	20 327
100 (212)	491	73 996	23 861
150 (305)	491	162 554	41 388
200 (392)	491	475 808	62 698
250 (482)	491	155 800	6 0119
300 (572)	491	97 575	34 019

Three-point bending fatigue test

2 Hz frequency

Tests carried out at a constant maximum flexural stress of $610 \text{ MN/m}^2 (88.5 \times 10^3 \text{ lbf/in}^2)$