EFFECT OF PRESTRESSING ON THE FATIGUE PERFORMANCE OF COMPRESSION SPRINGS

Mark P Hayes, Senior Metallurgist, Institute of Spring Technology, Sheffield. UK.
Tel: 44 114 252 7984 Fax: 44 114 252 7997 m.hayes@ist.org.uk.
Co-author Dr. Ing. Peter Thoma, Innotec, Marktredwitz, Germany.

Abstract

Prestressing of compression springs is known to be beneficial to their performance, but this study sets out to quantify that benefit. Drawn carbon, oil tempered silicon chromium steel and stainless steel spring wires have been prestressed to various lengths cold and hot to produce springs with none, a little and more prestressing. These springs were then fatigue tested in a systematic manner so that an accurate quantification of fatigue performance could be correlated with the prestressing conditions.

The results will enable greater sophistication to be achieved in the spring design process facilitating the design of lower weight springs without risk to reliability, and so will be of interest to nearly all spring manufacturing companies.

Introduction

The aim of this programme of work was to quantify the beneficial effect of prestressing on the fatigue performance of compression springs. It was the further aim to explain this benefit in terms of residual stress. The springs were manufactured from drawn carbon steel, oil tempered silicon chromium steel and drawn 302 stainless steel, each material being of good commercial quality. The springs were coiled, stress relieved and supplied ready for cold and hot prestressing in the laboratory.

The springs were fatigue tested at a range of applied stresses so that the life to failure was quantified at high operating stresses and the lowest operating stress at which no springs would fail was established.

Prestressing

The compression springs were made to a free length such that appreciable shortening would occur during the cold prestress process. Springs were load tested to confirm accurately the length at which they would shorten. Some were tested at lengths where no shortening would occur and these were described as ‘not prestressed’. Other springs were prestressed such that they were shortened a little, and others were prestressed to their block length so that the prestressing effect would be a maximum. Even further shortening or prestressing was accomplished by hot prestressing and / or hot setting the springs. None of the springs become significantly out-of-square as a result of prestressing.

Fatigue Testing

The springs were tested on forced motion mechanically driven test machines under conditions where the applied (corrected) stress was accurately known. The load cycle was sinusoidal and the test speed was set such that there were negligible additional stresses due to the dynamic loading. Each spring that failed was examined to ensure that its fatigue origin was at the inside surface of an active coil of the spring.

Residual Stress Testing

The springs were tested using X-Ray methods at the inside coil position. The incident X-Ray beam was rotated through 360° so as to establish both the direction and the magnitude of the residual stress. The result at the 45° (225°) angle to the wire axis was the most interesting since the applied torsional stress was a maximum at this position.

During prestressing the surface of the spring was plastically deformed in torsion and the residual stress imparted will be that present after springback after prestressing. The magnitude of the residual stress was measured but the depth of penetration was not.

Trail 1

A batch of compression springs made from EN 10270-2 SiCr VD quality was tested. The spring design is shown in Figure 1. These springs were tested

a) Not Prestressed.
b) Prestressed to 25mm.
c) Prestressed to block (20.5mm or 800N).

The fatigue results were as shown in Table 1

Batch - Not Prestressed

Corr. Stress Range / MPa	U/B at 10 million	Life to Failure
100-650	2	-
100-675	4	-
100-700	1	4,937,010
100-750	1	3,712,240
100-800	-	2 @ 3,570,250

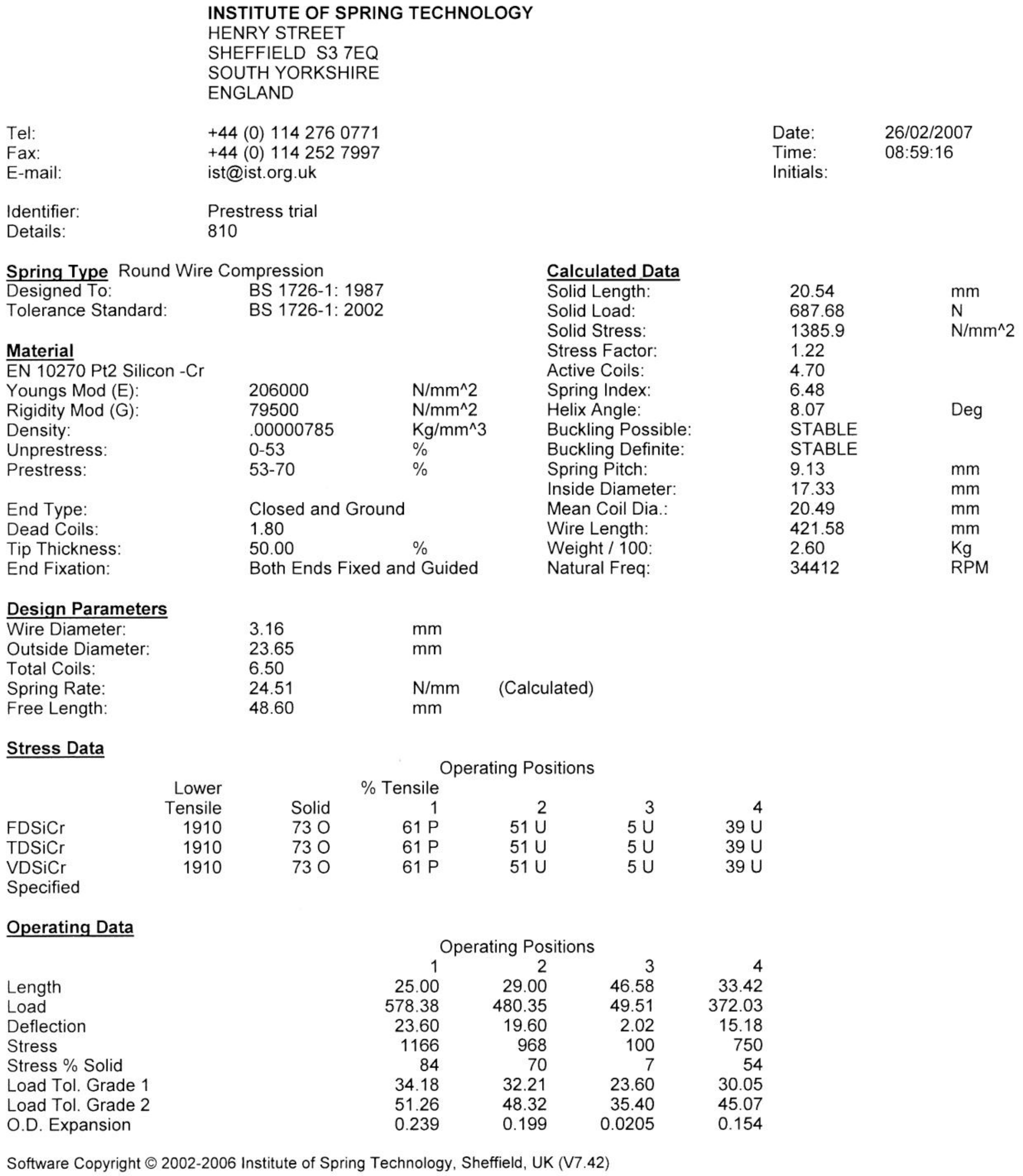
Batch - Prestressed to 25mm

Corr. Stress Range / MPa	U/B at 10 million	Life to Failure
100-700	2	-
100-750	2	-
100-775	2	6,580,280
100-775		8,634,600
100-800	-	6,496,180
100-800		2,125,080

Batch - Prestressed to Solid

Corr. Stress Range / MPa	U/B at 10 million	Life to Failure
100-750	4	-
100-775	2	4,969,280
100-775		6,186,110
100-800	1	3,290,610

Table 1 Fatigue Test Results



INSTITUTE OF SPRING TECHNOLOGY
HENRY STREET
SHEFFIELD S3 7EQ
SOUTH YORKSHIRE
ENGLAND

Tel:	+44 (0) 114 276 0771	Date:	26/02/2007
Fax:	+44 (0) 114 252 7997	Time:	08:59:16
E-mail:	ist@ist.org.uk	Initials:	

Identifier: Prestress trial
Details: 810

Spring Type Round Wire Compression

Designed To:	BS 1726-1: 1987	
Tolerance Standard:	BS 1726-1: 2002	

Material
EN 10270 Pt2 Silicon -Cr

Youngs Mod (E):	206000	N/mm^2
Rigidity Mod (G):	79500	N/mm^2
Density:	.00000785	Kg/mm^3
Unprestress:	0-53	%
Prestress:	53-70	%
End Type:	Closed and Ground	
Dead Coils:	1.80	
Tip Thickness:	50.00	%
End Fixation:	Both Ends Fixed and Guided	

Calculated Data

Solid Length:	20.54	mm
Solid Load:	687.68	N
Solid Stress:	1385.9	N/mm^2
Stress Factor:	1.22	
Active Coils:	4.70	
Spring Index:	6.48	
Helix Angle:	8.07	Deg
Buckling Possible:	STABLE	
Buckling Definite:	STABLE	
Spring Pitch:	9.13	mm
Inside Diameter:	17.33	mm
Mean Coil Dia.:	20.49	mm
Wire Length:	421.58	mm
Weight / 100:	2.60	Kg
Natural Freq:	34412	RPM

Design Parameters

Wire Diameter:	3.16	mm	
Outside Diameter:	23.65	mm	
Total Coils:	6.50		
Spring Rate:	24.51	N/mm	(Calculated)
Free Length:	48.60	mm	

Stress Data

	Lower Tensile	Solid	Operating Positions % Tensile 1	2	3	4
FDSiCr	1910	73 O	61 P	51 U	5 U	39 U
TDSiCr	1910	73 O	61 P	51 U	5 U	39 U
VDSiCr	1910	73 O	61 P	51 U	5 U	39 U
Specified						

Operating Data

	Operating Positions 1	2	3	4
Length	25.00	29.00	46.58	33.42
Load	578.38	480.35	49.51	372.03
Deflection	23.60	19.60	2.02	15.18
Stress	1166	968	100	750
Stress % Solid	84	70	7	54
Load Tol. Grade 1	34.18	32.21	23.60	30.05
Load Tol. Grade 2	51.26	48.32	35.40	45.07
O.D. Expansion	0.239	0.199	0.0205	0.154

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Figure 1

Fatigue Test Results

Prestressing improved the fatigue stress limit of these springs from 100-675MPa to 100-750MPa. No further benefit was accrued by prestressing beyond a length of 25mm, but the need to hot prestress was apparent, and this was included in subsequent trials.

Trial 2

Introduction

A batch of compression springs made from DIN 17224 302 stainless steel quality was manufactured. The springs had not been shot peened, but were of a design that would shorten appreciably when cold prestressed, as shown in Figure 2.

The springs were fatigue tested at corrected stress levels suitable to cause the springs to fail, and were then re-tested at stress levels at which they would survive.

Prior to fatigue testing the springs were

		Free Length
a)	Not prestressed	64.3mm
b)	Prestressed to 38mm	63.8mm
c)	Prestress to 30mm	62.7mm
d)	Prestressed to solid (i.e. 20.5mm approximately and 600N)	60.4mm
e)	Hot prestressed to 21.1mm at 200°C.	58.6mm
f)	Hot set to 22mm at 200°C.	55.6mm

The fatigue test results were as shown in Table 2.

Batch - Not Prestressed

Corr. Stress Range / MPa	U/B at 10 million	Life to Failure
100-450	4	
100-475	3	1 @ 1.69m
100-500	1	3 @ 396k, 463k & 900k
100-550	-	2 @ 221 & 258k
100-650	-	2 @ 94 & 112k
100-700	-	2 @ 100 & 106k

Batch - Prestressed to 38mm

Corr. Stress Range / MPa	U/B at 10 million	Life to Failure
100-475	4	
100-500	1	3 @ 2.17k, 6.19k & 9.10m
100-550	-	3 @ 854k
100-650	-	2 @ 311k
100-700	-	2 @ 117k

Batch - Prestressed to 30mm

Corr. Stress Range / MPa	U/B at 10 million	Life to Failure
100-500	4	-
100-525	2	2 @ 5.5m & 8.9m
100-550	-	2 @ 230k & 307k
100-600	-	2 @ 471k & 1.61m
100-700	-	2 @ 141k

Batch - Prestressed to Solid

Corr. Stress Range / MPa	U/B at 10 million	Life to Failure
100-500	6	-
100-525	3	1 @ 1.22m
100-550	1	1 @ 2.06m
100-600	-	2 @ 685k & 1.14m
100-700	-	2 @ 141k & 194k

Batch - Hot Prestressed

Corr. Stress Range / MPa	U/B at 10 million	Life to Failure
475	3	1 @ 2.17m
500	3	1 @ 6.71m
550	1	3 @ 0.43m, 1.10m & 3.11m

These springs appeared to have transverse, longitudinal and 45° cracks, as shown in figure 2

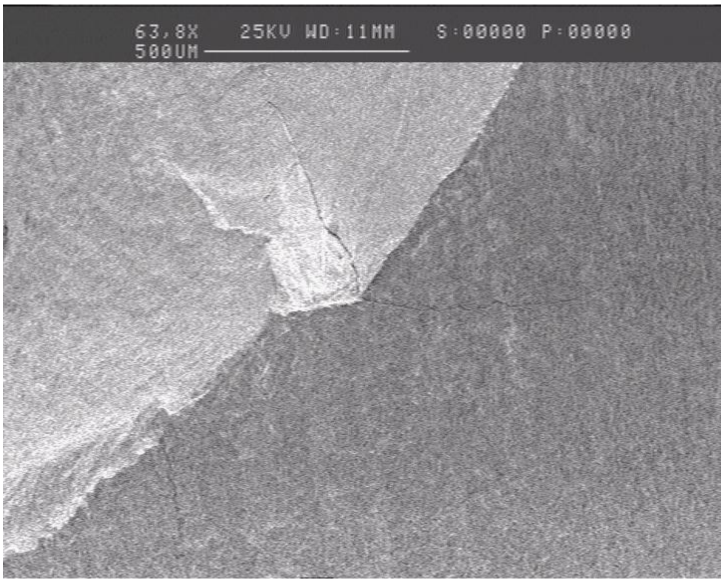


Figure 2

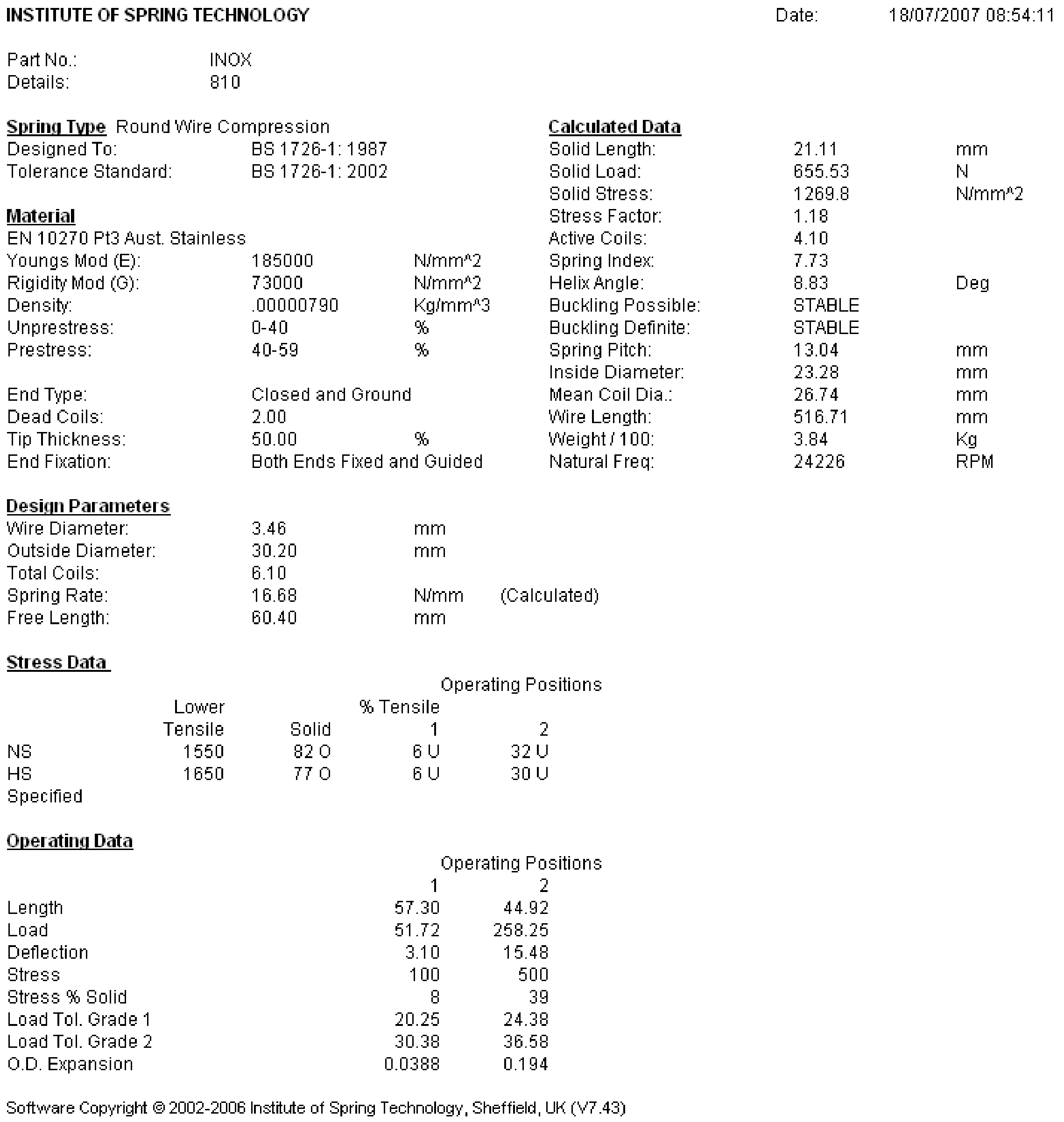
Batch - Hot Set

Corr. Stress Range / MPa	U/B at 10 million	Life to Failure
100-550	2	-
100-600	2	.

Table 2 Fatigue Test Results

Fatigue Test Results

Prestressing improved the fatigue stress limit of these springs from 100-450MPa to 100-500MPa. No further benefit was accrued by prestressing beyond a length of 30mm. The hot prestressed batch was worse than the cold prestressed due to cracks, as shown in Figure 2. The cause of the cracking is not yet understood. Hot setting improved the fatigue life significantly.



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Part No.: INOX
Details: 810

Spring Type Round Wire Compression			**Calculated Data**		
Designed To:	BS 1726-1: 1987		Solid Length:	21.11	mm
Tolerance Standard:	BS 1726-1: 2002		Solid Load:	655.53	N
			Solid Stress:	1269.8	N/mm^2
Material			Stress Factor:	1.18	
EN 10270 Pt3 Aust. Stainless			Active Coils:	4.10	
Youngs Mod (E):	185000	N/mm^2	Spring Index:	7.73	
Rigidity Mod (G):	73000	N/mm^2	Helix Angle:	8.83	Deg
Density:	.00000790	Kg/mm^3	Buckling Possible:	STABLE	
Unprestress:	0-40	%	Buckling Definite:	STABLE	
Prestress:	40-59	%	Spring Pitch:	13.04	mm
			Inside Diameter:	23.28	mm
End Type:	Closed and Ground		Mean Coil Dia.:	26.74	mm
Dead Coils:	2.00		Wire Length:	516.71	mm
Tip Thickness:	50.00	%	Weight / 100:	3.84	Kg
End Fixation:	Both Ends Fixed and Guided		Natural Freq:	24226	RPM

Design Parameters

Wire Diameter:	3.46	mm	
Outside Diameter:	30.20	mm	
Total Coils:	6.10		
Spring Rate:	16.68	N/mm	(Calculated)
Free Length:	60.40	mm	

Stress Data

			Operating Positions	
	Lower	% Tensile		
	Tensile	Solid	1	2
NS	1550	82 O	6 U	32 U
HS	1650	77 O	6 U	30 U
Specified				

Operating Data

	Operating Positions	
	1	2
Length	57.30	44.92
Load	51.72	258.25
Deflection	3.10	15.48
Stress	100	500
Stress % Solid	8	39
Load Tol. Grade 1	20.25	24.38
Load Tol. Grade 2	30.38	36.58
O.D. Expansion	0.0388	0.194

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Figure 3 Spring Design for Trail 2

Trial 3

A batch of springs was manufactured from 2.5mm diameter drawn carbon steel to EN 10270-1 DH quality. These springs were tested in the following conditions.

a) Not Prestressed.
b) Prestressed cold to solid.
c) Hot set at 180°C to solid + 1mm.

The fatigue test results were as shown in Table 3.

Batch - Not Prestressed

Corr. Stress Range / MPa	U/B at 1 million	Life to Failure
550	6	
615	6	
680	4	2 @ 7m
745		6 @ 180 - 600k
810		6 @ 170 - 500k
875		6 @ 170 - 500k
940		6 @ 80 - 300k

Batch - Not Prestressed

Corr. Stress Range / MPa	U/B at 10 million	Life to Failure
428	6	
489	6	
545	6	
600	4	2 @ 8m
650	-	6 @ 1 - 7m
704	-	6 @ 250k - 10m
754		6 @ 200k - 900k
816		6 @ 80k - 320k

Batch - Cold Prestressed

Corr. Stress Range / MPa	U/B at 10 million	Life to Failure
429	6	-
481	6	-
537	6	-
592	4	2 @ 6 - 9m
646	1	5 @ 2.5 - 9m
699	-	6 @ 550k - 7m
752	-	6 @ 400k - 1m
814	-	6 @ 250k - 900k

Batch - Hot Set

Corr. Stress Range / MPa	U/B at 10 million	Life to Failure
429	6	
479	6	
534	6	
590	6	
640	1	5 @ 3 - 9m
699	-	6 @ 600k - 3.3m
756	-	6 @ 800k - 2.2m
814	-	6 @ 200k - 800k

Fatigue Test Results

Cold prestressing did not improve the stress range with no breakages, but the life to failure at higher stresses was improved - generally double the life to first failure.

Hot setting improved the safe stress range with no failure but not the life to first failure compared with the cold prestressed.

Trial 4

A batch of springs was manufactured from 4mm diameter SiCrV wire with a tensile strength of 2130Mpa. The springs were tested in a similar way to those in Trail 3.

Batch - Not Prestressed

Corr. Stress Range / MPa		**U/B at 10 million**	**Life to Failure**
611	449-1061	6	-
686	412-1098	5	1 @ 3m
757	372-1129	1	5 @ 1.3m - 6m
839	335-1174	6	6 @ 500k - 7m
910	302-1212	6	6 @ 200k - 1.8m
985	259-1244	6	6 @ 80k - 600k

These results were much better than those for the similar material in Trial 1.

Batch - Cold Prestressed

Corr. Stress Range / MPa		**U/B at 10 million**	**Life to Failure**
525	418-944	6	-
590	389-979	6	-
651	352-1004	5	1 @ 9m
716	323-1039	4	2 @ 1.5m - 6m
781	287-1069	-	6 @ 600k - 7m
845	258-1102	-	6 @ 500k - 4m
907	229-1136	-	6 @ 60k - 1m
972	187-1159	-	6 @ 35k - 300k

Batch - Hot Set

Corr. Stress Range / MPa		**U/B at 10 million**	**Life to Failure**
521	413-933	6	-
588	379-968	5	1 @ 7m
650	349-999	5	1 @ 400k
716	320-1035	3	3 @ 2m - 10m
783	287-1072	1	5 @ 400k - 4m
843	259-1101	-	6 @ 400k - 2.2m
907	221-1129	-	6 @ 40k - 600k
971	196-1166	-	6 @ 50k - 500k

Fatigue Test Results

Neither cold nor hot prestressing improved the fatigue performance of this batch, but the fatigue performance as-received was very good - much better than the similar springs tested in Trial 1. For design purposes the fatigue performance after prestressing would not exceed that given for the as-received springs, which had a very low level of residual stress prior to prestressing.

Residual Stress Results

Using X-Ray methods at the inside surface of a central coil in compression springs the residual stress was measured. This was accomplished using an incident X-Ray beam that was rotated every 22.5° from the wire axis, which was designated 0°. The 45° results are shown here.

Results were as follows for drawn carbon steel

Residual Stress / MPa			
Angle	**As-coiled**	**Cold Prestressed**	**Hot Set**
0	+150	+220	+130
45	+220	+40	0
90	+120	+160	+20
135	-80	+260	+120
180	+150	+220	+200
225	+230	+50	+10
270	+120	+170	+20
315	-50	+330	+170
360	+150	+220	+130

It is clear that the pattern of residual stress has changed as a result of prestressing. The most important value is that at 45° or 225° since that is the angle at which the applied torsional stress is a maximum.

Cold prestressing has caused a change in residual stress at this angle of 180MPa and hot setting 220MPa. The residual tensile stress is reduced by this amount, and so the fatigue performance should improve, but the fatigue test results in Trail 3 show that the improvement in fatigue performance through hot setting is only about 50MPa.

For the oil tempered SiCrV wire the results were.

Angle	As-coiled	Cold Prestressed	Hot Set
0	100	+140	+120
45	120	-120	-120
90	30	+30	-10
135	30	+300	+200
180	120	+160	+140
225	150	-100	-100
270	40	40	0
315	40	+340	+250
360	100	+140	+120

Again the pattern of residual stress has been significantly changed by the prestressing processes. At the 45°/225° angles the residual stress has been made more compressive by 250MPa. In Trail 1 the fatigue stress limit was improved by 75MPa, but in Trial 4 almost no improvement in fatigue was realised.

Discussion

It was expected that prestressing would give benefits to compression spring fatigue performance, but this was realised in only three of the four trials.

The change in residual stress at 45° to the inside coil position was about 200MPa as a result of prestressing and this resulted in fatigue stress limit improvements of 0-75MPa.

Shot peening is also known to improve the fatigue performance of compression springs largely through the generation of residual compressive stresses. Typically a 700MPa residual compressive stress from shot peening improves the fatigue stress limit in each of the cold coiled materials being considered here by about 200-250MPa. Put in this context, the improvement in fatigue performance due to prestressing appears to be proportionally correct.

Conclusion

Compression springs made from high quality spring wires may be designed using higher operating stresses if they are prestressed in manufacture. This report provides guidance about the improvement in fatigue that can be expected when designing springs that are prestressed and / or are too small to shot peen and for which an improved fatigue performance is required.