THE SPRING RESEARCH AND MANUFACTURERS' ASSOCIATION

THE INFLUENCE OF SURFACE ROUGHNESS OF AS DRAWN WIRE UPON THE FATIGUE PERFORMANCE OF HELICAL COMPRESSION SPRINGS

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L.F. Reynolds, M.Sc. Tech., M.I.M.

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SUMMARY AND CONCLUSIONS

Fatigue tests using a replicated paired 't' test technique have been carried out on springs manufactured from BS 1408C R3 wires of equivalent diameter and mechanical properties but of varying surface textures. The wire surfaces were characterised by means of optical scanning electron microscopy and Rotary Talysurf techniques.

The fatigue tests have shown that no difference of any practical significance exists in the fatigue performance of springs manufactured from wires of equivalent mechanical properties but, for example, varying 'as drawn' surface textures ranging from 0.2 - 0.39 mm to 1.18 - 1.77 mm in terms of the Centre Line Average values obtained from a Rotary Talysurf instrument.

October 1978

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1. INTRODUCTION

The adverse effects of inadequate design, inadvertently introduced surface defects and generally poorly finished surfaces upon the fatigue properties of engineering components have been known for some time. In consequence of this, the engineering profession gives detailed attention to the design and manufacture of machine elements subject to fluctuating stresses, to ensure that the components do not fail prematurely in fatigue as a result of localised stress concentrations created by surface defects, e.g. machining, grinding and stamp marks, small fillet radii, etc.

In the absence of compressive stresses induced by suitable mechanical or thermal treatment, the initiation of fatigue cracks in metallic components is almost invariably a surface phenomenon. Consequently, the effects of stress raisers at the surface are particularly important, especially in the case of high strength materials operating at high stresses. It has been pointed out by Wilkinson(1) that springs almost invariably operate in either torsion and/or bending, and the region of maximum stress is therefore almost always at the surface. Furthermore, springs are normally designed to operate at relatively high stress levels, since their function is to act as storage reservoirs for elastic strain energy, in the most efficient and cost effective manner possible, within the limitations of the design. The possible adverse effects of surface finish or surface defects upon the fatigue performance of machine components therefore assumes particular importance in the case of mechanical springs.

Although the role of surfaces in fatigue crack initiation has been generally discussed in the literature(2), a large proportion of the work has been related to fatigue in rotating - bending, where the major stresses are alternately tensile and compressive in nature. Such work as has been carried out, however, indicates that the fatigue performance of metals increases progressively as the surface finish improves, in the order as forged, hot-rolled, machined, ground and polished(3).

It is well known, of course, that the detrimental effect of surface defects upon fatigue performance tends to become markedly more pronounced as the ratio (defect length/radius of curvature at defect tip) increases, as shown by the early work of Inglis(4), due to the effects of stress concentration,

i.e. Stress at crack tip, $\sigma_t = 2\sigma_n\sqrt{\frac{L}{R}}$ 1

where σ_n = Nominal stress, N/mm^2
L = Depth of crack, measured from surface
R = Radius of curvature at defect tip

Hence narrow cracks with a relatively small effective radius of curvature at the defect tip, such as could be produced during stress corrosion cracking, for instance, would generally be expected to be more harmful than the relatively shallow defects, of greater effective tip radius, produced by mechanical means such as drawing. Zimmerli(5), for example, found that aritificially produced scratches to a depth of about 12 μm (0.012 mm) had no significant effect upon the torsional fatigue performance of hardened and tempered valve spring wire, the composition of which approximated closely to BS 2803. On the other hand, similar sratches to a depth of 107 μm (0.107 mm) reduced the fatigue life to approximately 80% of that displayed by similar unscratched wires in the polished condition. Comparable results have been reported by other investigators in work on hard drawn carbon steels, whilst the harmful effects of seams, laps, etc. on fatigue performance are well known in the industry(6).

In practice, the fatigue performance of a material is markedly affected, not only by the quality of the surface finish, but also by the manner in which the particular surface is produced. The wire drawing process, for example, can result in the generation of residual tensile stresses of considerable magnitude at the wire surface, necessitating a low temperature heat treatment for their reduction before the components are put into service, if the fatigue life of the spring is not to be adversely affected(7).

Conversely, of course, surface treatments such as shot peening can significantly improve the fatigue performance of the components, as a result of the surface compressive stresses induced during the peening process(8), and they can therefore alleviate to some extent the detrimental effects of otherwise harmful defects.

In view of the many variables which can effect the fatigue performance of springs, therefore, it can be readily seen that any measurement of the effect of one variable upon the fatigue life of a component requires that all the work should be carried out in as similar a manner as possible on all the materials investigated. Such attention to detail will help to reduce the disparity of results which can arise due to the differences in surface residual stresses etc., in the absence of differences in the surface texture.

The measurement of surface texture was, of necessity, an integral part of the present work. A previous report has discussed the various means which are available for assessing the quality of wire surfaces(9).

Based on the conclusions of this work it was considered appropriate to characterise the wire surfaces qualitatively by both optical and scanning electron microscopy, and quantitatively by means of a rotary talysurf instrument, the principles of which have been described in the previous work(9).

It was decided that fatigue tests would be carried out on unpeened springs in the first instance and that, depending on the results of these tests, further work would be carried out on shot peened springs if necessary.

2. MATERIALS AND SPRING DESIGN

2.1 Material and Selection Criteria

Wire conforming to BS 1408C was selected for the work, since this was typical of a hard drawn material which would commonly be chosen for a dynamic application. Furthermore, the material was readily available from several member firms, thereby increasing the probability that wires showing suitable differences in 'as drawn' surface texture would be obtainable without undue difficulty.

Approximately thirty coils of readily available material were sampled for this work, the selection criteria being as follows:

a) Material of equivalent diameter should be available, showing differing degrees of 'as drawn' surface texture.

b) The tensile and torsional properties of wires of equal diameter should be very similar.

c) The wires should be of 'clean' steel with respect to non-metallic inclusions.

After considerable assistance from several member firms and following laboratory assessment, the wire finally chosen for the work consisted of BS 1408C R3 material in two diameters, 2.34 mm and 2.49 mm, with two levels of surface texture at each wire size.

Eddy current tests, which were carried out by a member firm, showed that the wires selected were all free from major longitudinal defects(10).

Based on the subsequent assessment of the wire surfaces (q.v.) the wires were identified as follows:-

2.49 mm diameter

Wire A (26): 'Smooth' surface finish
Wire B (22): 'Rough' surface finish

2.34 mm diameter

Wire C (25): 'Smooth' surface finish
Wire D (31): 'Rough' surface finish

The terms 'smooth' and 'rough' are purely relative descriptions of the surface finish, and are intended only for the purposes of identification rather than as a critical assessment of the surface texture. (The figures in parentheses refer to the original sample numbers of the wire coils, retained here for the purpose of future identification).

2.2 Spring Design and Manufacture

Springs were manufactured to the design shown in Table I. The solid stresses quoted are calculated from the standard relationship

$$\tau = \frac{G\delta K}{\pi c^2 n d} \qquad \ldots\ldots.2$$

where

G = Rigidity modulus, N/mm^2
d = Wire diameter, mm
n = Number of active coils
c = Spring index = $\frac{D}{d}$, where D = mean coil diameter, mm
K = Sopwith correction factor, = $\frac{c+0.2}{c-1}$
δ = Total deflection of spring to solid,
= $(L_o-(N-\frac{1}{2})d)$ where L_o = free length, mm,
and N is the total number of coils

The springs manufactured from the 2.49 mm and the 2.34 mm wires were coiled on a Wafios UFM 50 double point coiler and a Torrington 115A single point machine, respectively. In each case, all the springs made from the 'smooth' and 'rough' wires of equivalent diameter were coiled consecutively on the appropriate machine.

The four batches of springs produced were subsequently stress relieved simultaneously at 250°C/½ hour, after which they were end ground and prestressed to solid until no further decrease in free length occurred.

3. EXPERIMENTAL PROCEDURE

3.1 Mechanical Testing

In each case, duplicate samples of wire were tested in both the 'as drawn' and the low temperature heat treated condition.

3.1.1 Tensile testing

The tests were carried out on a vertical Amsler multi-range tensile testing machine equipped with an automatic stress-strain recorder. The latter was used in conjunction with an extensometer having a gauge length of 254 mm.

3.1.2 Torsion testing

Torsion tests were carried out using a Tinius Olsen machine which had a continuously variable angular velocity of 0-180°/min. Although this machine was equipped with an automatic torque/angular displacement recorder, this device constituted a relatively insensitive method of measuring the low torques applied to the wires. Appropriate readings were therefore taken manually throughout the test, since the results obtained were then suitable for more precise calculation and interpretation by regression analysis.
The torsional stresses and strains were calculated from the relationships:-

$$\text{torsional stress} = \frac{dT}{2J} = \frac{16T}{\pi d^3} \qquad \ldots\ldots\ 3$$

$$\text{and torsional strain} = \frac{d\theta}{2L} \qquad \ldots\ldots\ 4$$

where

d = Wire diameter, mm

T = Applied torque, N/mm

J = Second polar moment of area

$= \frac{\pi d^4}{32} \quad mm^4$

θ = Angular displacement, radians

L = Gauge length, $\gtrsim$ 100d mm

3.2 Characterisation of Wire Surfaces

The wire surfaces were characterised using the following techniques:-

- i Optical microscopy of transverse sections
- ii Low power stereoscopic microscopy
- iii Scanning electron microscopy
- iv Rotary Talysurf examination

All but the first technique required that the surface of the wire to be examined be thoroughly cleaned and decontaminated, in order that a true representation of the metal surface be obtained. This was particularly important in the case of the Talysurf examination, since it has been shown by Georges et al(11) that frictional contact between a surface contaminated with organic material and a moving stylus, under conditions of boundary lubrication, can lead to the accumulation of an organic 'agglomerate' at the stylus tip, thus reducing the sensitivity of the instrument to changes in the true profile of the surface.

The removal of organic films from the surface is also important if the material is to be examined under the scanning electron microscope, since such contamination can make it difficult to obtain consistent results. This is due to charging up and chemical cracking of the non-conducting film, forming carbon deposits on the area under examination by the electron beam.

3.2.1 Decontamination of Wire Surface

The method employed for cleaning the wires of surface scale and grease/soap contamination was based upon the caustic permanganate de-contamination procedures employed in industry, and which are normally used as a preliminary to acid pickling of materials(12,13).

Since it was important that the topography of the metal surface itself should not be attacked or altered, however, the following modified procedure was developed for the 'as drawn' wires.

1. Immersion for 5 minutes in a boiling solution of 10% sodium hydroxide, to saponify the greases into more easily removed soaps.

2. Immersion in a 10% solution of caustic permanganate (Progal 99CD) at 90°C, for 10 minutes.
   This solution can have two main effects,

   a) Conversion of the lower metal oxides (e.g. FeO) into the more readily acid-soluble higher oxides (e.g. Fe_2O_3, $FeO.Fe_2O_3$)

   and

   b) Mechanical loosening of the oxides at the solid/liquid interfaces, as a result of oxygen evolution due to the reduction of the permanganate to manganese dioxide.

3. Rapid wash in running hot water followed by acetone rinse.

4. Ultrasonic cleaning for 5 minutes, using trichlorethylene as the transfer medium, followed by clean trichlorethylene rinse.

5. Immersion for approximately 2 seconds in a cold solution of 10% hydrochloric acid in water, inhibited with 0.1% 'Kortohib' A220 to reduce or prevent attack of the metal surface by the dilute acid.

6. Rapid rinse in running hot water, followed by acetone rinse.

Wires prepared using this procedure gave consistent results when examined on both the Rotary Talysurf and the Scanning Electron Microscope instruments.

The cleaned and de-contaminated samples were subsequently stored in test tubes containing dried silica gel, to prevent re-contamination, rusting, etc., whilst awaiting further examination.

3.2.2 Optical microscopy

Transverse sections were taken of the four wires under investigation, and, after mounting in Bakelite, these were polished and examined, using a PME Olympus projection microscope.

3.2.3 Examination on binocular microscope

The cleaned and de-contaminated wires were examined on a Nachet EF50S stereoscopic binocular microscope for general appearance, surface damage, etc.

3.2.4 Scanning electron microscopy

The de-contaminated wire samples were mounted on an aluminium sample holder and were then examined on a Philips PSEM 500 scanning electron imcroscope, using an electron beam width of 640A (6.4×10^{-8} μm) and an electron anode accelerating potential of 25 kv.

Photographs of each wire surface were taken at magnifications between x80 and x1250, using Kodak Tri-X Pan Professional film, which was then developed for 9 minutes in Microphen solution at 20°C.

3.2.5 Rotary Talysurf examination

The surface texture of the cleaned wires were assessed by means of a Rotary Talysurf instrument manufactured by Rank Taylor Hobson Ltd, using facilities which were available in the Dept. of Mechanical Engineering Metrology Laboratory, University of Birmingham.

The specimens were mounted vertically in a small clamp, and were then centralised on the worktable of the instrument. The diamond stylus, which was mounted on a vertical spindle, was traversed around the sample circumference so as to maintain a constant, light pressure on the sample surface, whilst rotating about the longitudinal axis of the wire.

The vertical and horizontal magnifications of the instrument were set at suitable values (x 2000 and x 50 respectively), after which the instrument was operated to produce both surface profile charts of and Centre Line Average values for the wire surface being examined. Since the stylus could only traverse through a maximum angle of 200°, each wire was rotated through 180° to allow a second traverse to be carried out, and thus the full circumference of each wire sample could be assessed.

Two full circumferential scans were carried out for each wire, the Centre Line Average results being then assumed to lie within the range of the maximum and minimum values defined by the four readings thus obtained.

It should be pointed out that the Centre Line Average value is obtained by taking the average of a great many measurements of the heights of the peaks and valleys of the surface (measured from the mean surfaces), and is therefore <u>not</u> representative of <u>individual</u> 'defects' in the surface.

The Centre Line Average value can therefore be expressed as:-

$$\text{C.L.A. } (\mu\text{m}) = \frac{1}{\ell}\int_{0}^{\ell} |y|\,dx \qquad \ldots\ldots\ldots 5$$

i.e. the arithmetic sum of the total area, irrespective of sign, of the Talysurf curve about the mean line, per unit length of traverse

3.3 Dynamic Testing of Springs

3.3.1 Experimental design

Since the object of the work was to detect real differences in the fatigue performance of wires of differing "as drawn" ~~surface~~ texture rather than to produce ~~design~~ data, it was considered appropriate to use a replicated paired sample technique, which tends to reduce the effects of systematic experimental variation upon the results. Where significant differences in performance are small such experimental scatter can seriously impair the sensitivity of the more usual 't' test, which compares the estimated means and standard deviations of the two log life populations. In the paired 't' test, however, the samples to be compared (say, groups A and B) are tested simultaneously.

The tests are thus carried out on pairs of samples (A_1 B_1; A_2 B_2, etc.) under conditions which are as identical as the experimental technique will allow. The resulting data are transformed by taking the difference between the appropriate sample results, i.e. $A_1 - B_1$ etc. Hence, this difference should remain relatively constant for any set of experimental conditions, if the pairs of samples have been treated equally.

If we say (A-B) = x, then the differences should form a distribution with zero mean, on the assumption that no difference exists between the two sample populations.

The value of 't' can be calculated from the simplified relationship:-

$$t = \frac{\bar{x}\sqrt{N_p}}{S_x} \qquad \text{.......} \; 6$$

where

$\bar{x}$ = Mean of differences of log fatigue life obtained from paired data

S_x = Standard deviation of differences obtained from the paired log life data

N_p = Number of pairs considered, i.e. A_1 B_1; A_2 B_2 ---- A_N B_N

The difference between the two sets of data can then be assessed by testing the resulting value of 't' at the appropriate level of significance for (N_p-1) degrees of freedom, via the Null Hypothesis that there is no significant difference between the two sets of data, i.e. H_o; $\bar{x} = 0$. (Standard tables for the percentage points of the 't' distribution are published and widely available).

This statistical replication technique is well documented in the literature, which should be consulted for further information(14,15).

3.3.2 Fatigue testing

A forced motion multiple station fatigue testing machine operating at 25 Hz was used for the tests.

A limited amount of initial work was carried out on a number of springs, selected at random, for each category of wire tested. From the results of this work, the form of the S/N curve could be ascertained, and a series of suitable stress levels could be chosen for the main body of paired statistical tests to be carried out. The paired tests were peformed at an initial stress of 100 N/mm^2, and at maximum stress levels of 700 - 950 N/mm^2 in 50 N/mm^2 steps.

For the series of experiments on the springs manufactured from wires of equal diameter but differing surface textures, at least five pairs of springs were tested at each of the chosen levels of maximum stress. The total number of pairs tested was thus arranged to give a maximum of 25 pairs of broken springs for the statistical analysis of the limited life data.

Although this paired replication technique is not generally suited to the production of fatigue data with statistical levels of confidence, such data has been produced from the appropriate fatigue results in the present instance.

The springs were load tested to determine the deflections necessary for the minimum and maximum stresses required, the load having been calculated from the relationship:-

$$P = \frac{\pi d^3 \tau}{8DK} \qquad \ldots\ldots\ 7$$

where

P = Load, N
d = Wire diameter, mm
τ = Torsional stress, N/mm^2
D = mean coil diameter, mm
K = Sopwith correction factor, = $\frac{c+0.2}{c-1}$

All the fractured springs were examined on the binocular microscope to ensure that the results used for the statistical analysis were obtained from springs which had not failed due to gross surface defects, spring end-grinding marks, etc.

4. RESULTS

The results of the tensile and torsion tests are given in Tables II and III respectively. The Centre Line Average (C.L.A.) values obtained from the Rotary Talysuf instrument are given in Table IV.

The data for the paired fatigue tests are shown in Tables V and VI, whilst the results of the paired 't' test analysis are shown in Table VII.

Figure 1 shows the optical appearance of the wires after chemical and ultrasonic cleaning, whilst the optical photomicrographs, electron scanning images and the Talysurf traces are shown in Figures 2 - 5.

The fatigue data are shown plotted in Figures 6 and 7 for the springs manufactured from the 2.49 mm and 2.34 mm diameter wires, respectively.

5. DISCUSSION

The tensile results given in Table II indicate that the materials all conformed to the relevant specification with respect to the tensile strengths of the 'as drawn' wires.

The elastic properties of the wires of equivalent diameter, after low temperature heat treatment at 250°C/½ hour, were very similar in both tension and torsion, and hence the wires of equivalent size could be justifiably assumed to possess very similar mechanical properties.

The optical appearance of the clean wires, shown in Fig. 1, inidcates that the wires exhibiting a 'smooth' finish, samples A (2.49 mm) and C (2.34 mm), had polished and highly reflective surfaces, whilst those showing a 'rough' finish, samples B

(2.49 mm) and D (2.34 mm) had surfaces with a dull, matt appearance. Thus, it is relatively easy to discern a rough wire from a smooth one, simply by cleaning as above.

Transverse microsections of the wires are shown in Fig. 2-5, and these indicate the nature of the surface irregularities, together with the oxides present within the depressions on the surfaces of the 'rough' wires, B and D.

The appearance of the surfaces can be seen in more detail on the images obtained via the scanning electron microscope shown in Figs. 2-5, which also show the appropriate traces obtained from the Rotary Talysurf examination. The differing surface textures of the 'smooth' and the 'rough' wires are readily apparent, and are particularly pronounced in the case of samples C and D (Figs. 4 and 5), respectively.

In terms of the Centre Line Average values shown in Table IV, it can be estimated very approximately that the ratio C.L.A. (rough): C.L.A. (smooth) had a value of about 3 for the 2.49 mm (samples A and B) wires and 5 for the 2.34 mm (samples C and D) wires.

An estimate of the greatest observed depth of surface irregularity, which is likely to have the largest effect on the fatigue performance of the springs, can be obtained by appropriate measurement of these features on the relevant photomicrographs and Talysurf traces. Such measurements were made, and the following values of the greatest irregularity depth were obtained.

Wire identification	Greatest observed depth of irregularity	
	Optical examination, μm	Talysurf examination, μm
A	2.2	2.5
B	7.0	4.0
C	3.3	2.3
D	11.0	6.5

This comparison serves to emphasise that the Talysurf measurement is an *average* measurement of surface texture, whereas, from the nature of fatigue, the harmful defects are likely to be isolated large defects. These would not be individually registered by the C.L.A. value, although they would appear on the Talysurf trace itself.

The results of the paired 't' tests carried out on the appropriate wires are shown in Table VII, whilst the relevant data are shown plotted in Figs. 6 and 7. It can be seen from the table that there was no difference at the 95% level of significance in the fatigue performance of springs manufactured from 2.49 mm diameter wires of differing 'as drawn' surface texture.

In the case of the 2.34 mm diameter wires, the difference in fatigue performance of the springs made from material of differing surface texture was just significant at the 95% level. Since the paired 't' test is quite a sensitive method of assessing difference in behaviour, however, it is not considered likely that this slight difference would have any real value in practice.

In terms of surface irregularities, therefore, these results confirm that the presence of possibly oxide-filled surface irregularities to a depth of at least 11 μm has no detrimental effect of any measurable significance upon the fatigue performance of springs made from BS 1408C R3 wires.

This result may be partially explained in terms of the stress concentration factor postulated by Inglis(4).

i.e. Stress at crack tip, $\sigma_t = 2\sigma_n\sqrt{\frac{L}{R}}$ 1

Estimates from the optical photomicrographs suggested that the radius of curvature of the crack tip had a value of approximately 2 μm. Since the maximum observed defect depth was 11 μm, the stress at the defect tip can be estimated by substitution of the appropriate figures in the above relationship. Such a calculation suggests that the stress at the defect tip would be about 5 times the nominal tensile component of the maximum torsional stress applied to the spring. It may thus be that local plastic yielding at the tip of the small defects observed in the present instance, with a stress concentration factor of 5, may have been sufficient to significantly reduce the magnitude of the otherwise harmful stresses to a level where they would be ineffective in readily initiating fatigue cracks early in the life of the spring.

By comparison, a surface defect such as a seam, etc., may well have a depth in excess of 100 μm, and if the radius of curvature at the defect tip is reasonable assumed to be of the order of 0.5 μm, then the stress at the defect tip can be shown by the above formula to be in the order of 30 times the nominal tensile component of the torsional stress. The degree of plastic yielding necessary to reduce such a stress concentration could well result in the formation of a highly work-hardened, brittle region at the defect tip, with consequent intitation of fatigue cracks leading to the early failures often observed in such defective springs.

Since the surface texture of the 'as drawn' wires had an insignificant effect on the fatigue performance of the springs, the effect of shot peening was not investigated, as the peening process would only be expected to further reduce any differences arising from the surface irregularities in the wire.

6. CONCLUSIONS

1. Thorough decontamination is necessary to ensure representative and reproducible examination of the wire surfaces by both the scanning electron microscope and the Rotary Talysurf instrument. In the present instance, a combination of alkaline permanganate treatment followed by chemical and ultrasonic cleaning was found to be suitable for this purpose.

2. The work has shown that, all other things being equal, there is no differende of any practical significance in the fatigue performace of springs of the same design

manufactured from BS 1408C between wires of different 'as drawn' surface texture, where the maximum observed defect depth is of the order of 11 μm.

7. RECOMMENDATIONS

Following upon the conclusions of this work, it would be interesting to assess the effects of surface deterioration, rusting, etc. upon the fatigue performance of springs manufactured from carbon steel wires, since it is possible that wires of a more highly polished nature may corrode less readily than wires of a rougher texture, stored under similar conditions.

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TABLE I DESIGN DATA FOR BS 1408C, R3 SPRINGS

Design parameters	Wire identification	
	Wires A and B	Wires C and D
Wire diameter, mm	2.49	2.34
Mean coil diameter, mm	19.92	18.72
Total coils	5.5	5.5
Active coils	3.5	3.5
Free length, mm, after end grinding and pre-stressing	33.85	31.81
Solid stress, N/mm^2	1170	1170

TABLE II TENSILE PROPERTIES OF BS 1408C, R3 WIRES*

Wire condition	Wire		Tensile Properties						
	Diam. mm	Ident.	R_m N/mm^2	L. of P. N/mm^2	R_p 0.05 N/mm^2	R_p 0.1 N/mm^2	R_p 0.2 N/mm^2	R. of A %	Elong. %
As received	2.49	A	1800	560	1000	1190	1400	55	3.5
		B	1820	580	1050	1250	1470	52	4
	2.34	C	1880	600	1090	1290	1480	54	5
		D	1790	770	1250	1410	1560	46	5
L.T.H.T. 250°C/½ hr	2.49	A	1860	1330	1620	1700	1780	52	4.5
		B	1880	1170	1560	1670	1740	50	6.5
	2.34	C	1930	1310	1670	1760	1830	55	6
		D	1850	1420	1740	1800	1840	53	5.5

* All results are the average of two tests.

TABLE III TORSIONAL PROPERTIES OF BS 1408C, R3 WIRES*

Wire Condition	Wire		Torsional properties, N/mm^2			
	Diam. mm	Ident.	L. of P.	0.1% P.S.	0.2% P.S.	G
As Received	2.49	A	500	770	860	7.5×10^4
		B	420	710	800	7.5×10^4
	2.34	C	500	720	820	7.5×10^4
		D	570	810	900	7.7×10^4
L.T.H.T. 250°C/½hr	2.49	A	900	1070	1130	7.8×10^4
		B	820	1030	1090	7.9×10^4
	2.34	C	930	1120	1180	7.8×10^4
		D	920	1090	1150	7.8×10^4

* All results are the average of two tests.

TABLE IV RESULTS OF SURFACE TEXTURE MEASUREMENTS BY ROTARY TALYSURF FOR BS 1408C, R3 WIRE

Wire Data		Centre Line Average Value (C.L.A.)* µm
Ident.	Diam. mm	
A	2.49	0.16 - 0.67
B	2.49	0.75 - 1.61
C	2.34	0.20 - 0.39
D	2.34	1.18 - 1.77

* The Centre Line Average (C.L.A.) value is the numerical assessment of the average height of the irregularities constituting surface texture.

TABLE V PAIRED FATIGUE TESTS RESULTS ON SPRINGS MANUFACTURED FROM 2.49 mm DIAMETER WIRE.

INITIAL STRESS 100 N/mm^2

Maximum Stress N/mm^2	Fatigue results N cycles for spring groups	
	N_Ax 10^6	N_Bx 10^6
950	.225	.171
"	.198	.189
"	.189	.135
"	.162	.135
"	.117	.162
900	.216	.162
"	.153	.216
"	.225	.216
"	.306	.225
"	.243	.189
850	.324	.321
"	.432	.252
"	.279	.414
"	.396	.379
"	.351	.333
800	.627	1.051
"	1.434	2.02
"	.525	.402
"	.463	.431
"	.365	.715
750	3.402	9.417
"	1.802	4.326
"	11.52 U/B	7.152
"	2.969	3.012
"	1.55	11.211
700	12.51 U/B	12.505 U/B
"	3.027	12.505 U/B
"	6.253	8.011
"	7.795	11.604 U/B
"	12.47 U/B	11.604 U/B

TABLE VI PAIRED FATIGUE TESTS RESULTS ON SPRINGS MANUFACTURED FROM 2.34 mm DIAMETER WIRE.

INITIAL STRESS 100 N/mm^2

Maximum Stress N/mm^2	Fatigue results N cycles for spring groups	
	N_Cx 10^6	N_Dx 10^6
950	.144	.117
"	.162	.171
"	.198	.144
"	.198	.234
"	.324	.180
900	.441	.09
"	.072	.333
"	.261	.234
"	.432	.234
"	.441	.342
850	.114	.273
"	.891	.324
"	.756	.387
"	.54	.558
"	.062	.273
800	.269	.99
"	.954	.603
"	3.098	.747
"	5.346	1.08
"	2.631	.747
750	.648	1.035
"	6.858	.882
"	2.574	1.008
"	2.997	1.944
"	1.499	.495
700	11.27 U/B	6.037
"	7.391	1.79
"	12.42	8.355
"	.747	11.13 U/B
"	11.28 U/B	3.152

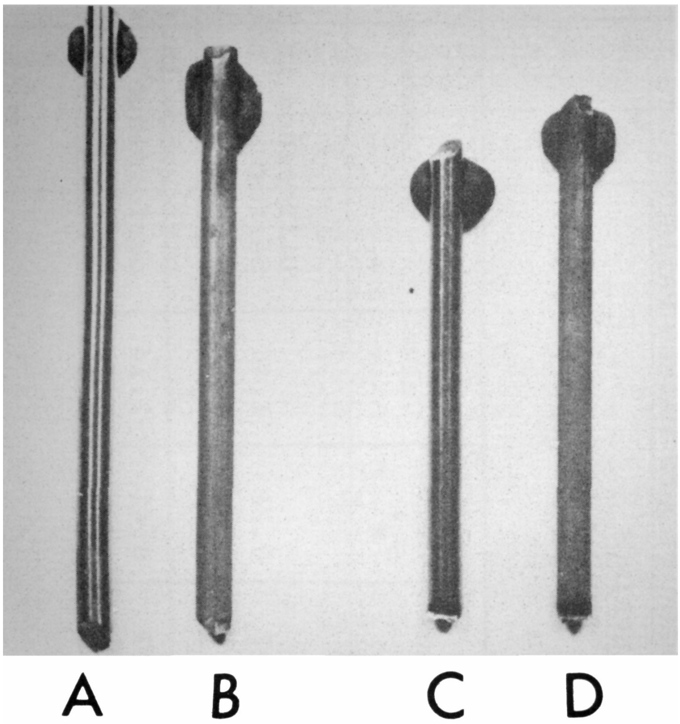
TABLE VII ANALYTICAL RESULTS AND INTERPRETATION OF PAIRED FATIGUE TESTS CARRIED OUT ON BS 1408C, R3 SPRINGS

Wire Data		Total Pairs N_p	Mean Value $\bar{x}$*	Std. Dev. S_x*	t Value	Comments
Groups compared	Diam. mm					
A/B	2.49	25	-0.07	0.24	1.46	Difference in fatigue performance not significant at 95% level
C/D	2.34	27	0.17	0.41	2.14	Difference in fatigue performance just significant at 95% level

*$\bar{x}$ = (Log N_A - Log N_B) and (Log N_C - Log N_D0 respectively,

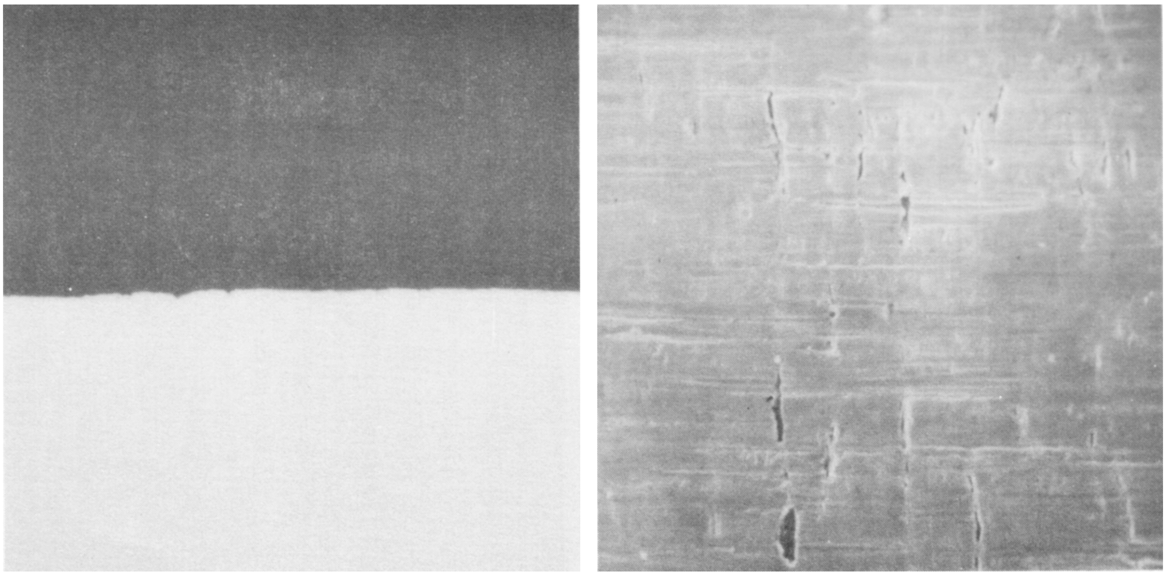
= The mean of the differences in log fatigue life obtained from the paired data

S_x = Standard deviation of the differences obtained from the paired log life data



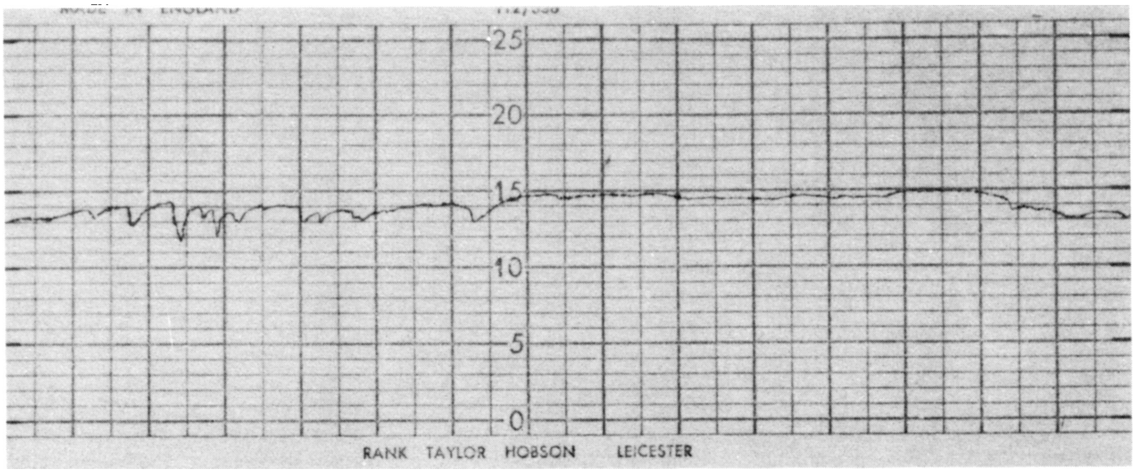
Optical Photomacrograph x 2

Fig. 1 Appearance of Patented cold drawn BS 1408C wires after decontamination



(i)
Transverse Cross Section
x 450

(ii)
Scanning Electron Image
x 320

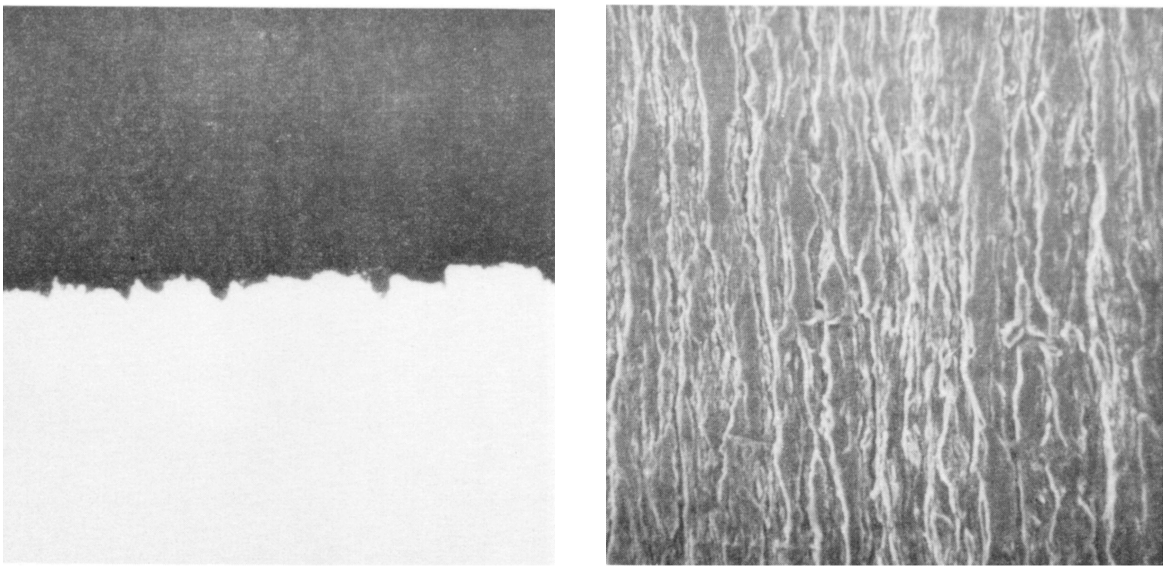


(iii)

Talysurf Trace: Vertical Magnification x 2000
Horizontal Magnification x 50
C.L.A. value: 0.16-0.67 μm

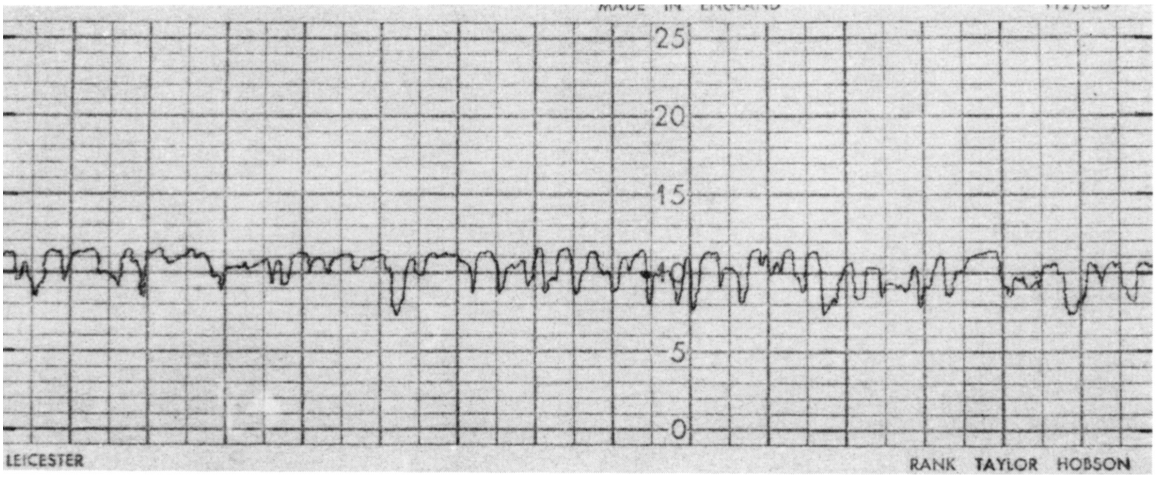
Fig. 2 Patented cold drawn BS 1408C wire surfaces

Sample A: 2.49 mm



(i)
Transverse Cross Section
x 450

(ii)
Scanning Electron Image
x 320

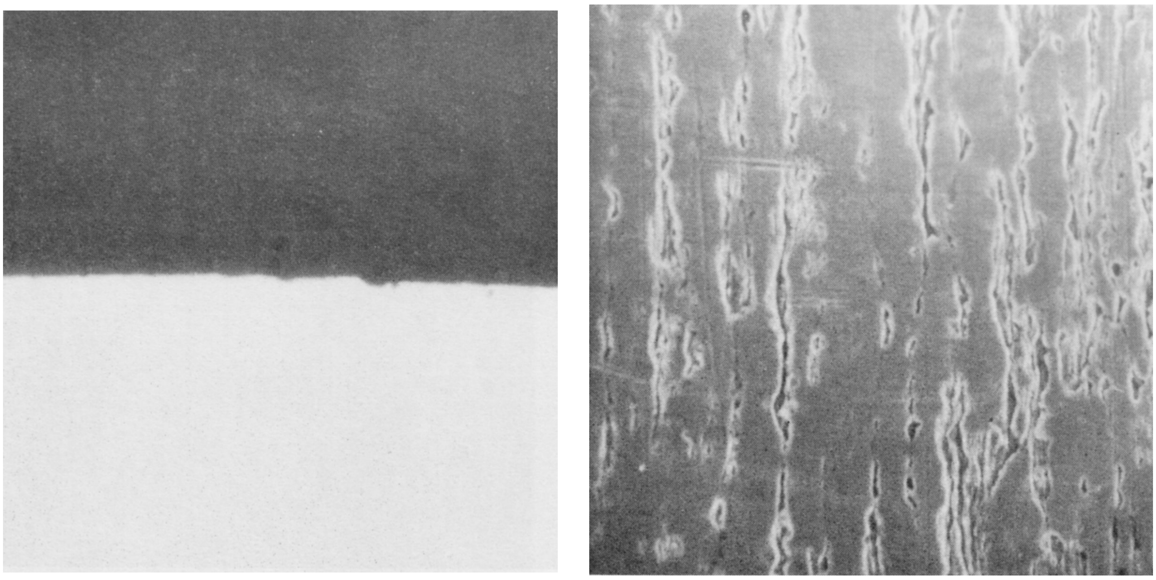


(iii)

Talysurf Trace: Vertical Magnification x 2000
Horizontal Magnification x 50
C.L.A. value: 0.75-1.61 μm

Fig. 3 Patented cold drawn BS 1408C wire surfaces

Sample B: 2.49 mm



(i)

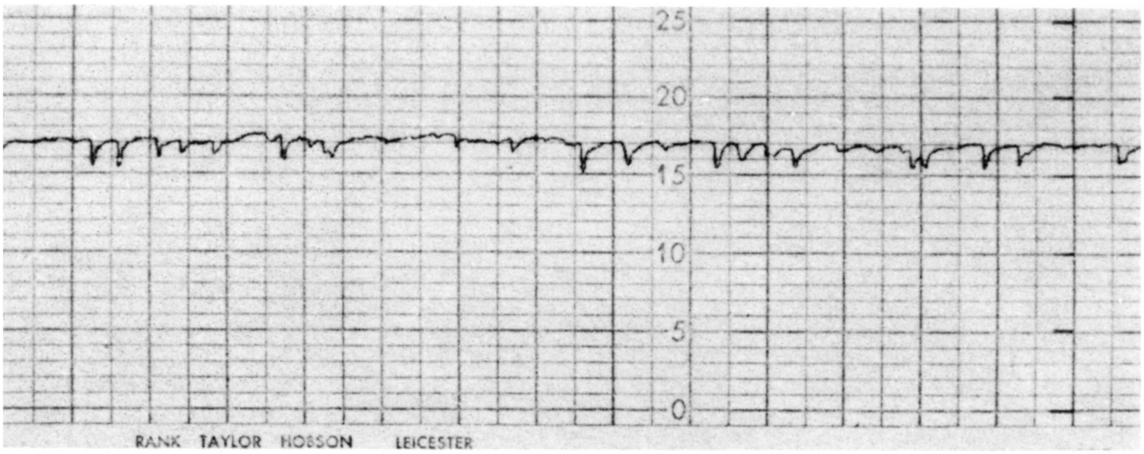
ransverse Cross Section

x 450

(ii)

Scanning Electron Image

x 320

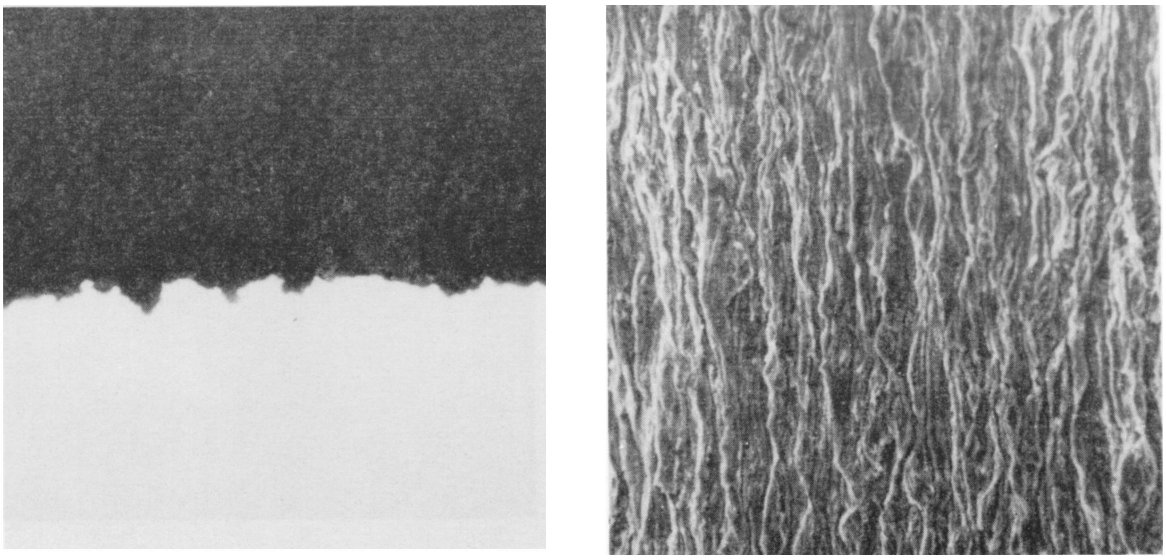


(iii)

Talysurf Trace: Vertical Magnification x 2000
Horizontal Magnification x 50
C.L.A. value: 0.20-0.39 μm

Fig. 4 Patented cold drawn BS 1408C wire surfaces

Sample C: 2.34 mm

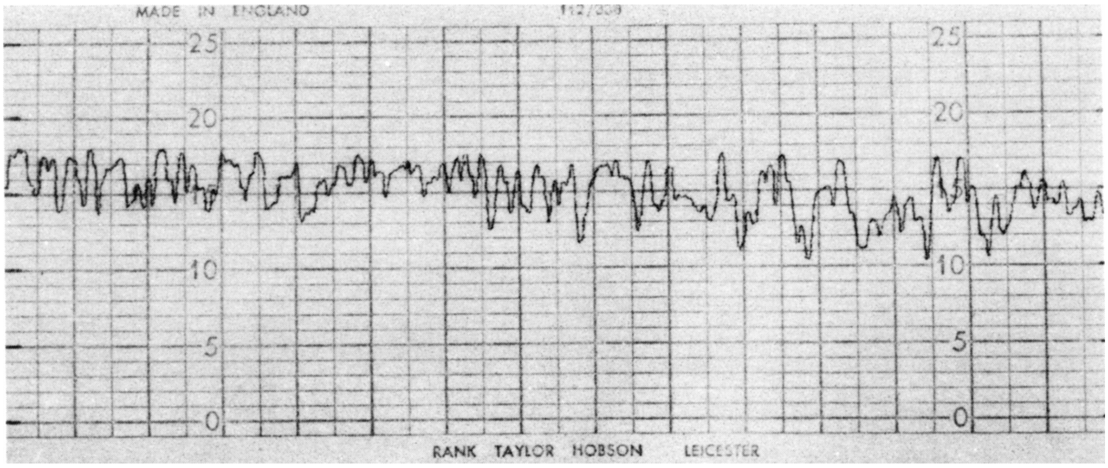


(i)

Transverse Cross Section
x 450

(ii)

Scanning Electron Image
x 320



(iii)

Talysurf Trace: Vertical Magnification x 2000
Horizontal Magnification x 50
C.L.A. value: 1.18-1.77 μm

Fig. 5 Patented cold drawn BS 1408C wire surfaces

Sample D: 2.34 mm

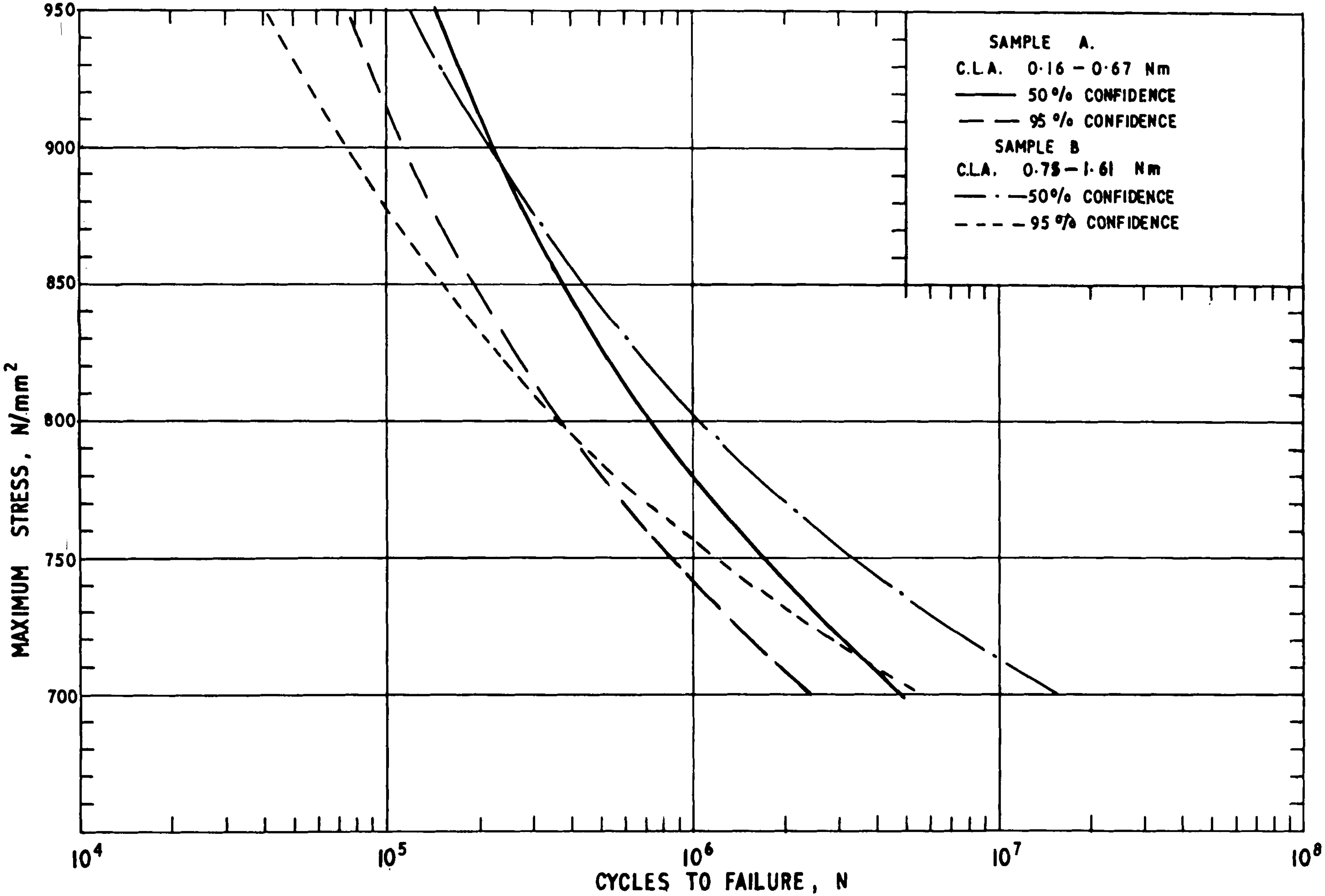


FIG. 6 FATIGUE CURVES FOR SPRINGS MANUFACTURED FROM 2·49 mm DIA. WIRE TO BS. 1408 C. R3. INITIAL STRESS 100 N/mm^2

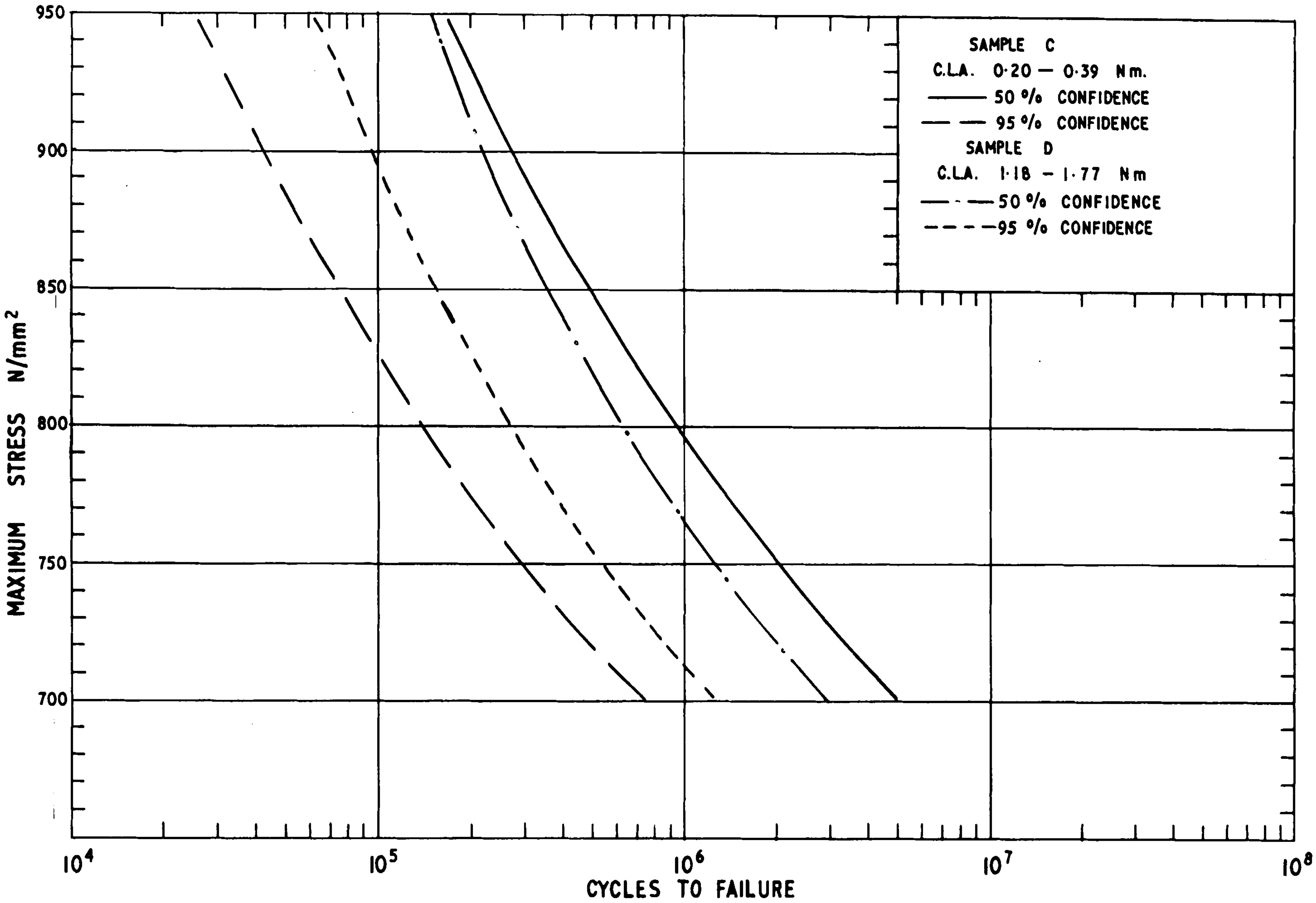


FIG. 7. FATIGUE CURVES FOR SPRINGS MANUFACTURED FROM 2·34 mm DIA. WIRE TO BS 1408.C. R3 INITIAL STRESS 100 N/mm^2