THE SPRING RESEARCH AND MANUFACTURERS' ASSOCIATION

THE EFFECT OF SURFACE ROUGHNESS, ELECTROPOLISHING AND SHOT PEENING ON THE FATIGUE PROPERTIES OF AUSTENITIC STAINLESS STEEL SPRINGS

BY

M O'Malley, B.Sc.

Report No 369

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SUMMARY

Fatigue tests have been carried out on helical compression springs made from 2.64 mm diameter BS 2056 302S26 wire with varying degrees of surface roughness. The surface quality was assessed using optical and scanning electron microscopy techniques.

The results have shown no practical difference in the fatigue properties of the springs for the three surface qualities except at high stress levels, where springs of good surface quality exhibit slightly better fatigue properties than springs of poor surface quality. However, electropolishing of the wire improved the fatigue performance of the spring considerably, but not to as great an extent as shot peening. In view of these results, electropolishing would appear to have commercial implications in situations where shot peening would not be effective ie for springs of small wire diameter or coil pitch.

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1. INTRODUCTION

The adverse effects of poor surface finish on the fatigue properties of engineering components have been well known for a considerable length of time. As the initiation of fatigue cracks in metallic components occurs primarlily at the surface, particluar care is taken in the manufacture of highly stressed parts to ensure that localised stress concentrating features, such as machining marks etc, are not produced on the surface.

In springs, the region of maximum stress is almost always situated at the wire surface. It is, therefore, reasonable to assume that surface quality could have considerable effects on the fatigue performance of springs. A previous investigation carried out by the Association [(1)] found that surface roughness did not significantly effect the fatigue properties of patented hard drawn carbon steel springs. However, the effects of surface quality on the fatigue performance of stainless steel wire springs have not been fully investigated, even though stainless steel is known to have worse levels and to exhibit wider variations in surface roughness. With these considerations in mind, there would appear to be a greater probability of the fatigue properties of stainless steel springs being adversely affected by poor surface quality.

The surface quality of engineering components can be considerably improved by polishing. Mechanical polishing is known to lead to improvements in fatigue properties as a result of the cold working of, and introduction of compressive stresses into, the surface layers of the component.[2] However, mechanical polishing of an intricately shaped component, such as a helical spring, is obviously impossible. Electropolishing, on the other hand, can be carried out on any component, regardless of shape, and has become well established as a commercial finishing process for aluminium alloys and stainless steels. Although electropolishing does not introduce any additional stress into the component, it may effect the fatigue properties by removing beneficial surface stresses.

The electropolishing process involves dissolution of the metal surface in a suitable electrolytic bath. Due to the electro-chemical nature of the process, dissolution at surface irregularities occurs at a higher rate than at the general surface, thus leading to a leveling of the wire topography.

2. MATERIAL USED IN THE INVESTIGATION AND SPRING DESIGN

The work was carried out using hard drawn stainless steel wire to the BS 2056 302S26 specification. All the stainless steel wires in the Association's stock, and in the wire stocks of a number of member firms, with diameters between 2.5 and 3.0 mm were examined using optical microscopy and scanning electron microscopy techniques. From the results of both qualitative and quantative assessments of their surface roughness, three wires of 2.64 mm diameter were chosen for the investigation as being representative of good, average and poor surface quality. Transverse cross sections and scanning electron micrographs of the three wire qualtities are shown in Figures 1 to 3.

The chemical compositions and mechanical properties for the three wires are given in Tables I and II respectively. It will be seen from Table II that the tensile strengths of the good and average surface quality wires were approximately 4% and 2% above the maximum specified tensile strength. However, as the inaccuracies of measurement of the wire diameter and breaking load introduce a possible error of approximately 2% in the tensile strength determination, the average surface quality wire could be deemed to comply with the specified range, although the good quality wire would still be slightly overstrength. The errors in the tensile strength were calculated using standard error theory.

The wires were coiled to a common spring design, the parameters of which are given in Table III. After coiling, the springs were given a low temperature heat treatment of 450°C for 1/2 hour and then end ground.

Fifty springs of the average surface roughness grade were then sent to Poligrat Limited, where they were given the standard commercial electropolishing treatment for stainless steel. Figure 4 shows a transverse section and a scanning electron micrograph of the electropolished wire which indicates the improvement in surface quality. A further set of 50 average surface quality springs were shot peened in the Association's Tilghman Wheelbrator machine using CS 330 shot to give an almen arc rise of 0.54 mm A2, and were then stress relieved at a temperature of 220°C for 30 minutes. Sixteen of the electropolished springs were also given an identical peening treatment to that described above.

Finally, all 6 batches of springs were cold prestressed until stable.

3. FATIGUE TESTING

Fatigue tests were carried out on a 8 station forced motion testing machine operating at 25 Hz. All the tests were carried out at an initial stress level of 100 N/mm^2.

For the three wire grades (ie good, average and poor surface quality), 4 springs of each grade were tested at varying maximum stress levels commencing at 800 N/mm^2 and decreasing in 50 N/mm^2 increments until the fatigue limit for each grade was attained. The fatigue limits were chosen as the stress level at which 50% or more of the springs tested survived beyond 10^7 cycles. The maximum and minimum lengths necessary to give the required stress range were determined by load testing the springs. From the results obtained it was possible to produce S/N curves for each of the three surface qualities and these are shown in figures 1 to 7.

Fatigue tests were then carried out on the electropolished, shot peened and electropolished and shot peened springs. Batches of 4 springs were tested at varying maximum stress levels commencing at 600 N/mm^2 (the stress at which a life of approximately 10^6 cycles had been obtained for the average surface quality springs) and increasing in 50 N/mm^2 increments until stress levels were eventually reached when failures occurred. The results of these tests are given in Figures 8 to 10 for the electropolished, shot peened and electropolished and shot peened springs respectively.

For each of the six batches of material, the broken springs were examined optically and suitable fracture examples prepared for further examination using the scanning electron microscope.

4. STATISTICAL ANALYSIS AND DISCUSSION OF RESULTS

As can be seen from figures 1 to 3, the surface quality of the stainless steel wires varied considerably. An estimate of the greatest observed depth of surface irregularity, which was likely to have the largest effect on the fatigue performance of the springs, was obtained for each of the three wire qualities by measurement of these features on the mounted cross sections. The results were:

Wire Identification	Greatest Oberseved Depth of Irregularity (m)
Good quality	4.6
Average quality	20.3
Poor quality	30.5

Comparison of Figure 2 (the average surface quality material) with Figure 4 (its electropolished counterpart) demonstrates the effectiveness of electropolishing in smoothing the wire topography and removing surface irregularities. Unfortunately, a coiling mark was introduced on the inside of the coil during the coiling process, and this feature has been smoothed and shallowed, but not completely removed by electropolishing. A schematic representation of this is presented in Figure 4 (iii).

4.1 Fatigue Results

The fatigue results for each wire quality were statistically analysed to produce 50% and 95% confidence limits and these are presented on the S/N curves.

The fatigue limit determined from the testing was found to be identical for all three wire qualities; in each case the limit was determined as 450 N/mm^2. However, the poor quality wire had no springs surviving 10^7 cycles above this limit, whereas some springs of the good surface quality were surviving up to a maximum stress level of 550 N/mm^2.

The limited life results for all three wire qualities were then analysed using an ANOVA technique. It was found that, at lower stress levels (ie just above the fatigue limit) there was no difference in the limited life fatigue performance for the three wire qualities. However, at high stress levels there was a significant difference between the wire qualities, with the fatigue life improving with improved surface quality.

Electropolishing improved the fatigue resistance of the springs, but to a lesser extent than shot peening. The fatigue limit for the average surface quality springs was raised to approximately 700 N/mm^2 by electropolishing and to 800 N/mm^2 by shot peening. Carrying out both electropolishing and shot peening processes on the springs resulted in similar fatigue performance to that obtained by shot peening only.

4.2 Scanning Electron Microscopic Examination of Fractures

The scanning electron microscope examination of the various fatigue fracture samples for the three wire qualities revealed that the failure mechanism for hard drawn stainless steel springs was similar to that observed in hard drawn carbon steel springs.[3,4] The majority of the fatigue cracks initiated in longitudinal shear (stage I) at the inside region of the first active coil of the springs. The longitudinal shear crack propagated to a depth of between 60 and 120 m before transferring into 45° tensile propagation (stage II) and eventually leading to rapid fracture of the spring (see figures 11 to 13).

For the good surface quality wire, it was observed that on two springs the stage I initiation had occurred at 90° to the wire axis (see Figure 14). This type of failure initiation was seen by Koizumi and his colleagues[4] in their investigation of oil tempered silicon chromium valve spring fatigue, but has not previously been observed in hard drawn wires at SRAMA.

It was noticed that, for all three wire qualities, the stage I shear crack was made up of 2 distinct regions: a smooth featureless zone adjacent to the wire surface had below this a slightly roughened zone (see Figures 11 (ii) and 12 (ii)). The depth of the smooth zone was measured and was found to be consistent with the surface intrustion depth measured on the cross sections. It would, therefore, appear that the smooth zone corresponds to the surface break up and the roughened zone corresponds to the crack propagation zone.

In previous work at SRAMA(3), it was indicated that 95% of the fatigue life was occupied in initiating and propagating the stage I crack. However, as the results of the scanning electron microscopical examination indicates that the surface roughness has acted as a pre-existing stage I shear crack, it would seem reasonable to assume that the poor quality wire (which had deeper surface roughness) would fail significantly earlier than the good quality wire due to the reduction in crack propagation time. This was not borne out in practice, however, as there was no difference in fatigue life at low stresses, and at high stresses the difference was not substantial.

A few early failures were experienced by each of the three wire qualities. For the average and poor surface quality springs, the scanning electron microscopical examination revealed that the fractures had intiated at some form of pitting on the wire surface (see Figure 15), the cause of which was not apparent. However, there was no obvious cause for the early failure experienced with the good surface quality wire.

The electropolished springs had all failed by the standard stage I and stage II failure mechanism, but all the initiation sites were associated with a coiling mark which the electropolishing process had failed to completely remove (see Figure 16). It would seem a distinct probability that this coiling mark has acted as a stress raiser and caused earlier failure of the electropolished springs than might otherwise have occurred if the springs had been completely defect free. Further testing of electropolished springs completely free of any form of surface marking would be necessary to prove or disprove this assumption.

The few failures which had occurred in the shot peened springs had all initiated at the wire surface with the standard stage I longitudinal shear crack which had then propagated through the shot peened surface layer prior to transferring to stage II failure. This is clearly demonstrated in Figure 17, where the depth of the shot peened layer is easily identifiable and was found to extend to a depth of approximately 0.13 mm.

4.3 Implication of Results

The significance of the results for the electropolished springs is immediately apparent. In addition to providing a surface with a cosmetically pleasing appearance, the process can be applied to springs where the wire diameter or coil pitch are too small for affective shot peening.

5. CONCLUSIONS

1. Surface roughness has negligible effects on the fatigue properties of hard drawn stainless steel springs.

2. Scanning electron micrographs of the fracture surfaces indicated that the failure mechanism was similar to that observed in cold drawn carbon steel wires.

3. Electropolishing improves the fatigue properties of stainless steel springs, but not to as great an extent as shot peening. The fatigue limit was raised from 450 N/mm^2 to 700 N/mm^2 by electropolishing and to 800 N/mm^2 by shot peening.

4. The electropolished spring failures had all initiated at the only stress concentration feature present on the wire surface.

6. RECOMMENDATIONS

As all the failures in the electropolished springs were associated with the coiling mark on the wire surface, further testing of defect free electropolished springs could indicate whether the maximum benefits of this process have been realised.

7. REFERENCES

1. Reynolds, L F "The Influence of Surface Roughness of as Drawn Wire upon the Fatigue Performance of Helical Compression Springs" SRAMA Report 298, Oct, 1978.

2. Cina, B "The Effect of Surface Finish on Fatigue". Metallurgia, 1957, 55, pp 11-19.

3. Reynolds, L F "Fatigue Failures of Light Springs. Final Report On the Reasons for the Scatter of Fatigue Results obtained for Compression Springs made from BS 5216 ND3 wire". SRAMA Report No 358, May, 1983.

4. Koizumi, Y, Shimoda, H and Saito T, unpublished information.

TABLE I CHEMICAL COMPOSITIONS

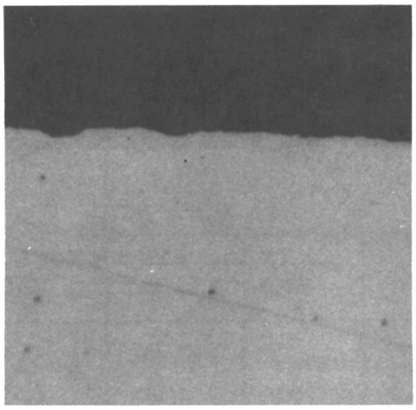
	Composition (%)						
	C	Si	Mn	S	P	Ni	Cr
Specified BS 2056 302S26	0.12 max	1.00 max	2.00 max	0.030 max	0.045 max	7.5-10.0	17.0-19.0
Good	0.091	0.52	0.44	0.011	0.018	8.6	18.0
Average	0.041	0.52	1.61	0.013	0.029	8.6	17.9
Poor	0.092	0.35	0.62	0.003	0.023	8.1	17.5

TABLE II MECHANICAL PROPERTIES

	Rm N/mm^2	L of P N/mm^2	$Rp_{0.05}$ N/mm^2	$Rp_{0.1}$ N/mm^2	$Rp_{0.2}$ N/mm^2
Specified for BS 2056 302S26 Grade II	1570-1810	-	-	-	-
Good	1885	545	1140	1330	1550
Average	1850	805	1315	1505	1720
Poor	1730	745	1225	1405	1585

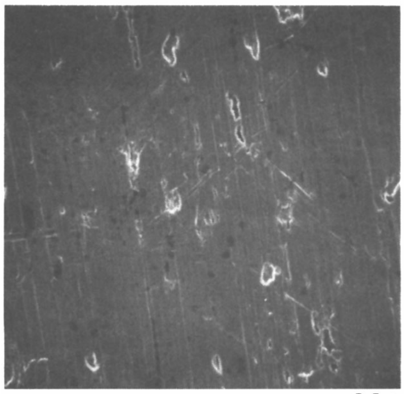
TABLE III SPRING DESIGN

Spring Parameter	
Wire diameter (mm)	2.64
Mean coil diameter (mm)	18.48
Spring index	7.0
Total coils	5.5
Active coils	3.5
Free length after end grinding	33.0
LTHT and prestressing (mm)	
Solid stress (N/mm^2)	1095
End type	Closed and ground



(i) x500

Transverse cross section.

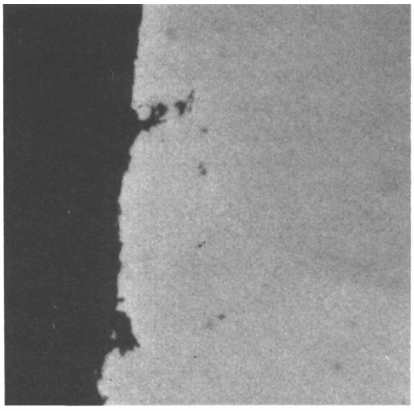


(ii) X330

Scanning electron micrograph.

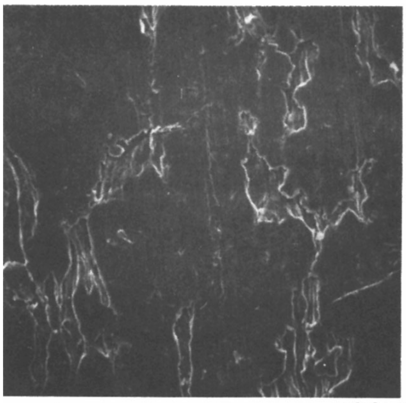
Fig 1

Hard drawn BS 2056 302S26 wire of good surface quality



(i) X500

Transverse cross section.



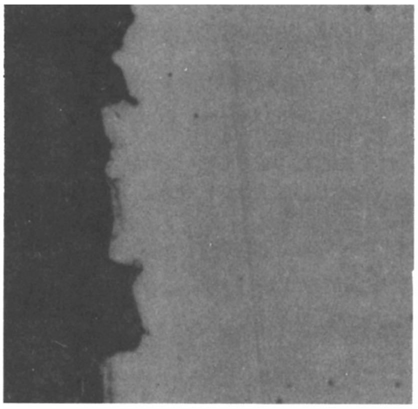
(ii) X330

Scanning electron micrograph.

Fig 2

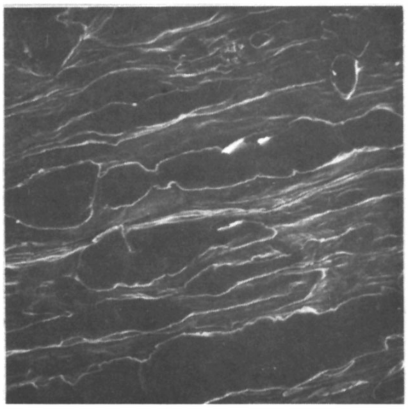
Hard drawn BS 2056 302S26

wire of average surface quality



(i) X500

Transverse cross section.



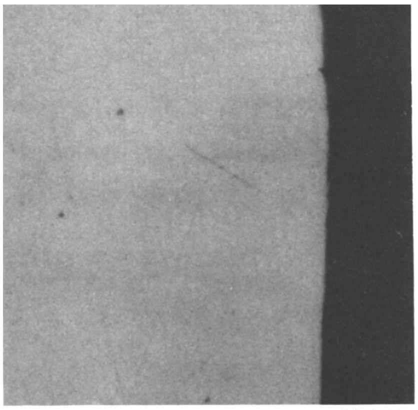
(ii) X330

Scanning electron micrograph.

Fig 3

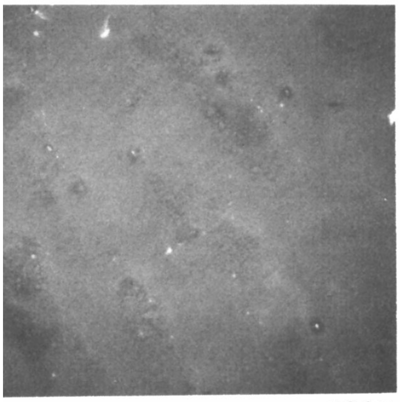
Hard drawn BS 2056 302S26

wire of poor surface quality



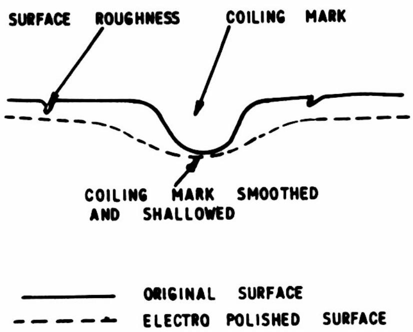
(i) X500

Transverse cross section.



(ii) X330

Scanning electron micrograph.



(iii)

Schematic representation of surface removal by electropolishing.

Fig 4

Electropolished BS 2056

302S26 wire

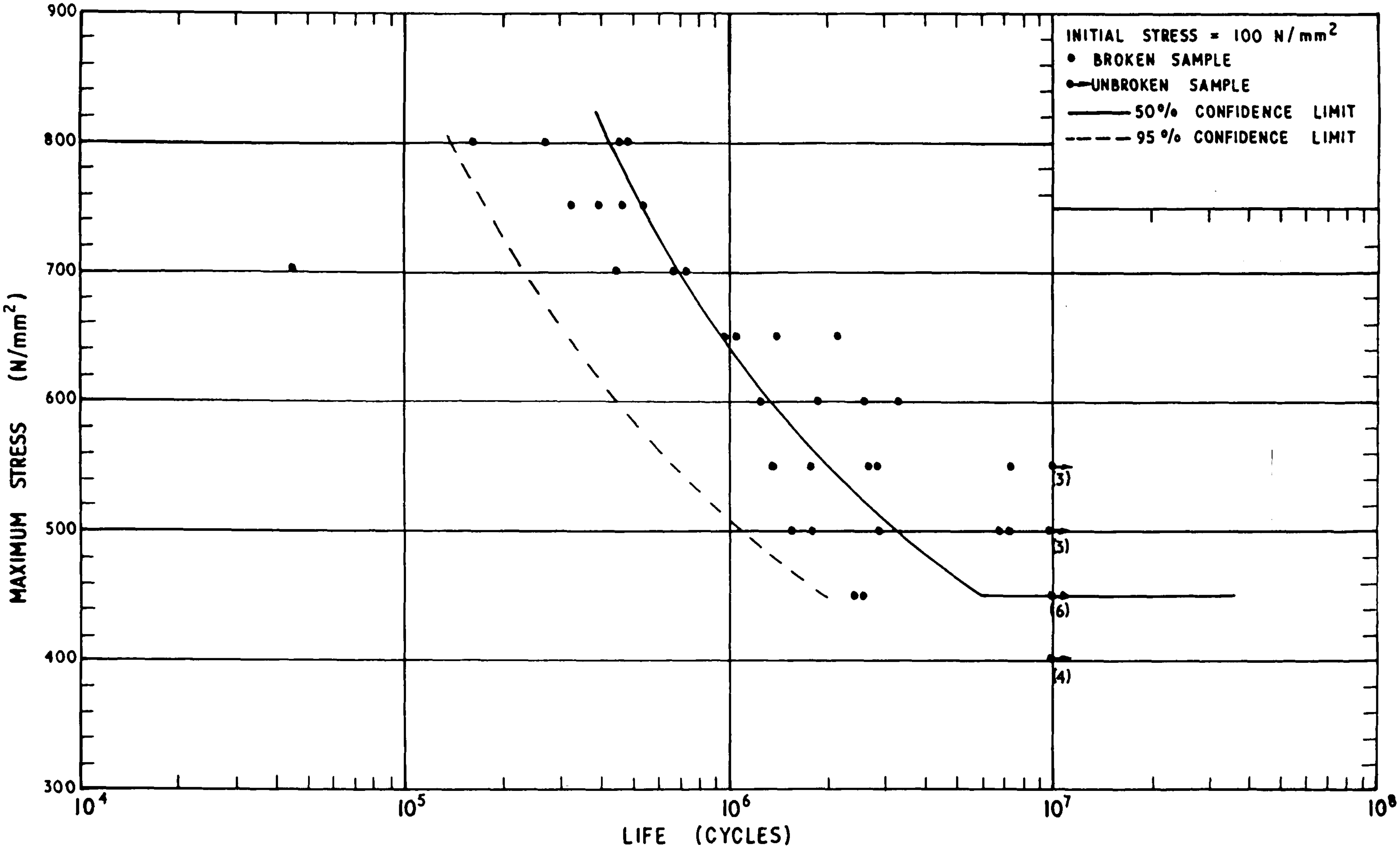


FIG. 5. FATIGUE CURVE FOR SPRINGS MADE FROM BS 2056 302S26 WIRE OF GOOD SURFACE QUALITY.

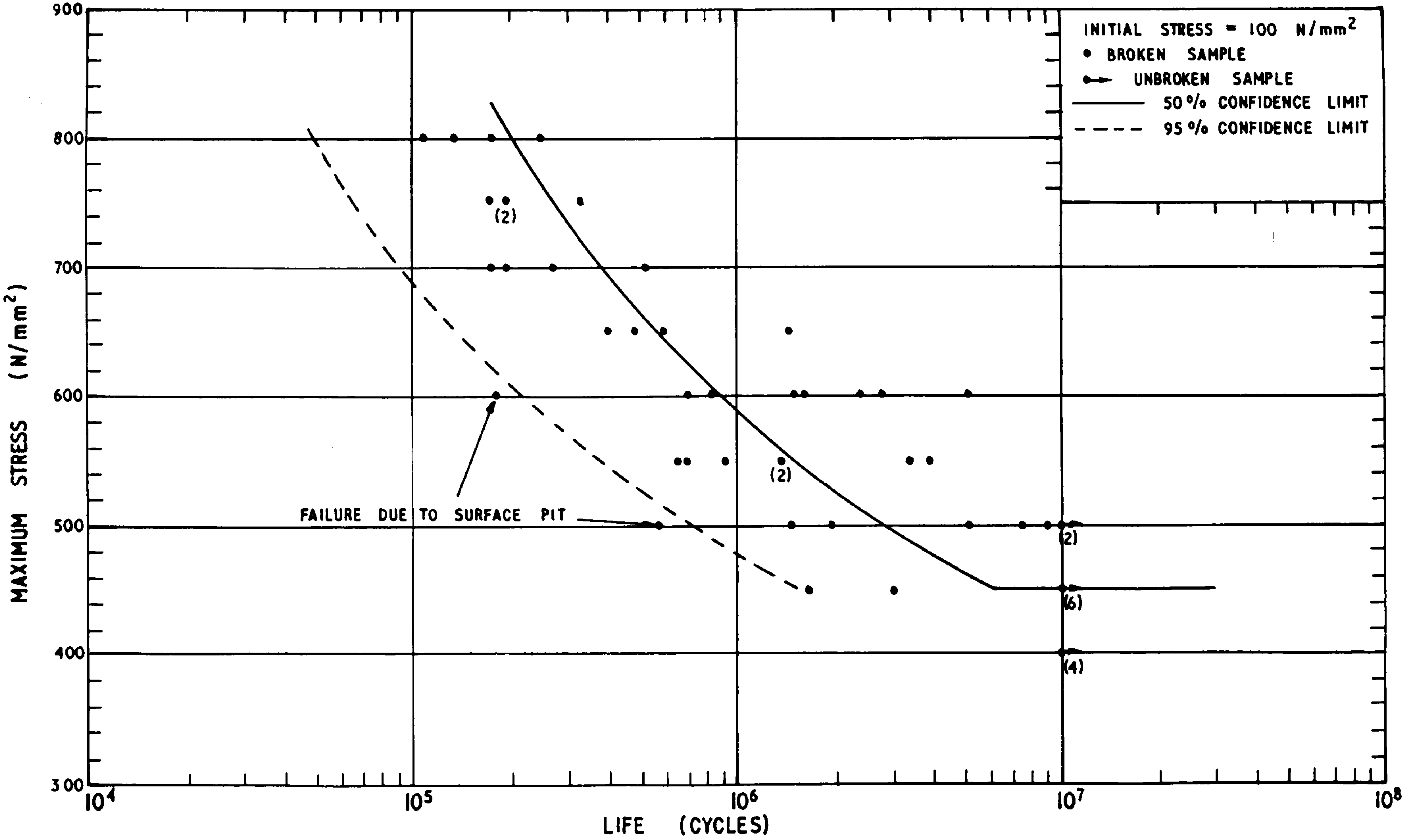


FIG. 6. FATIGUE CURVE FOR SPRINGS MADE FROM BS 2056 302 S26 WIRE OF AVERAGE SURFACE QUALITY.

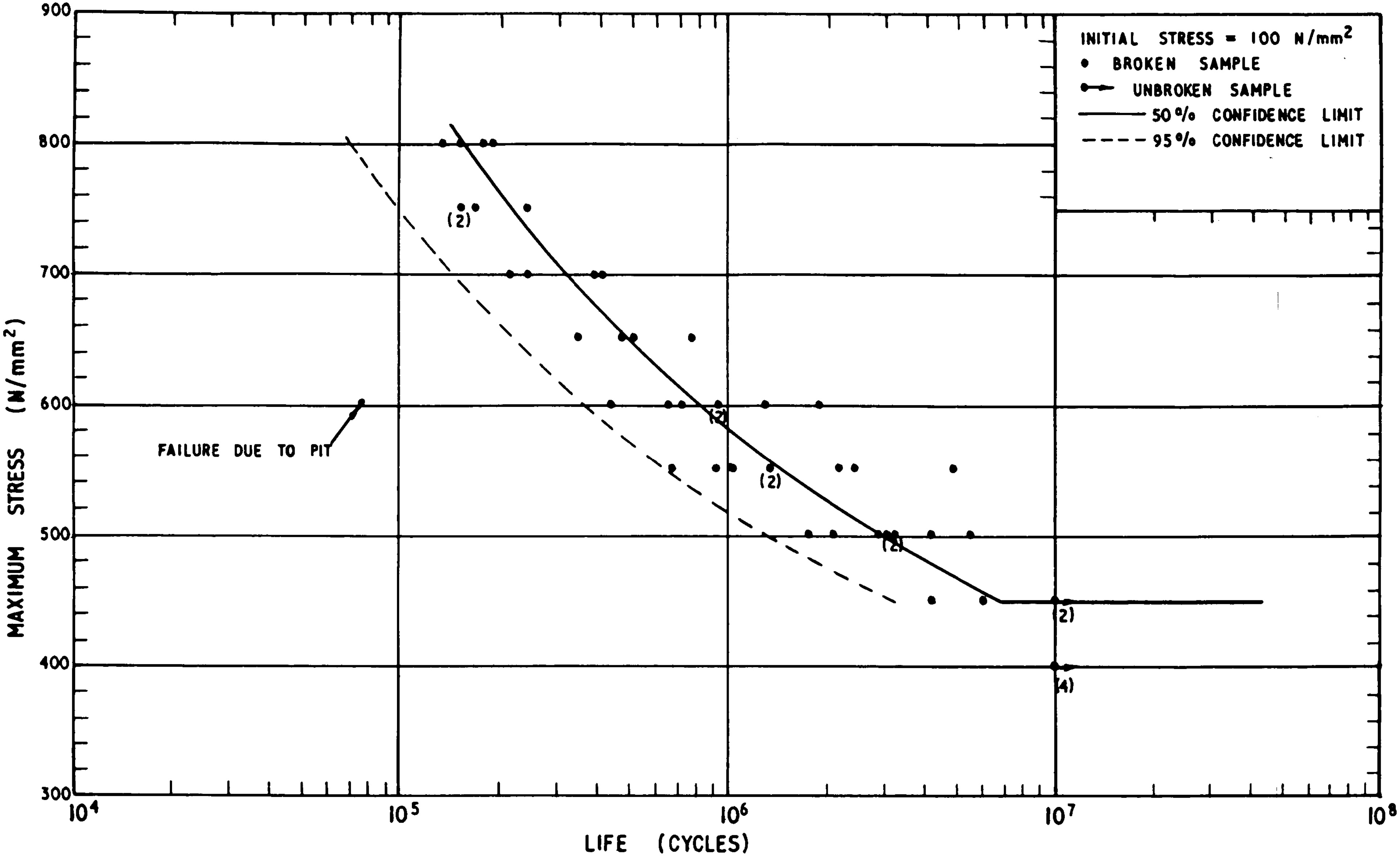


FIG. 7. FATIGUE CURVE FOR SPRINGS MADE FROM BS 2056 302S26 WIRE OF POOR SURFACE QUALITY.

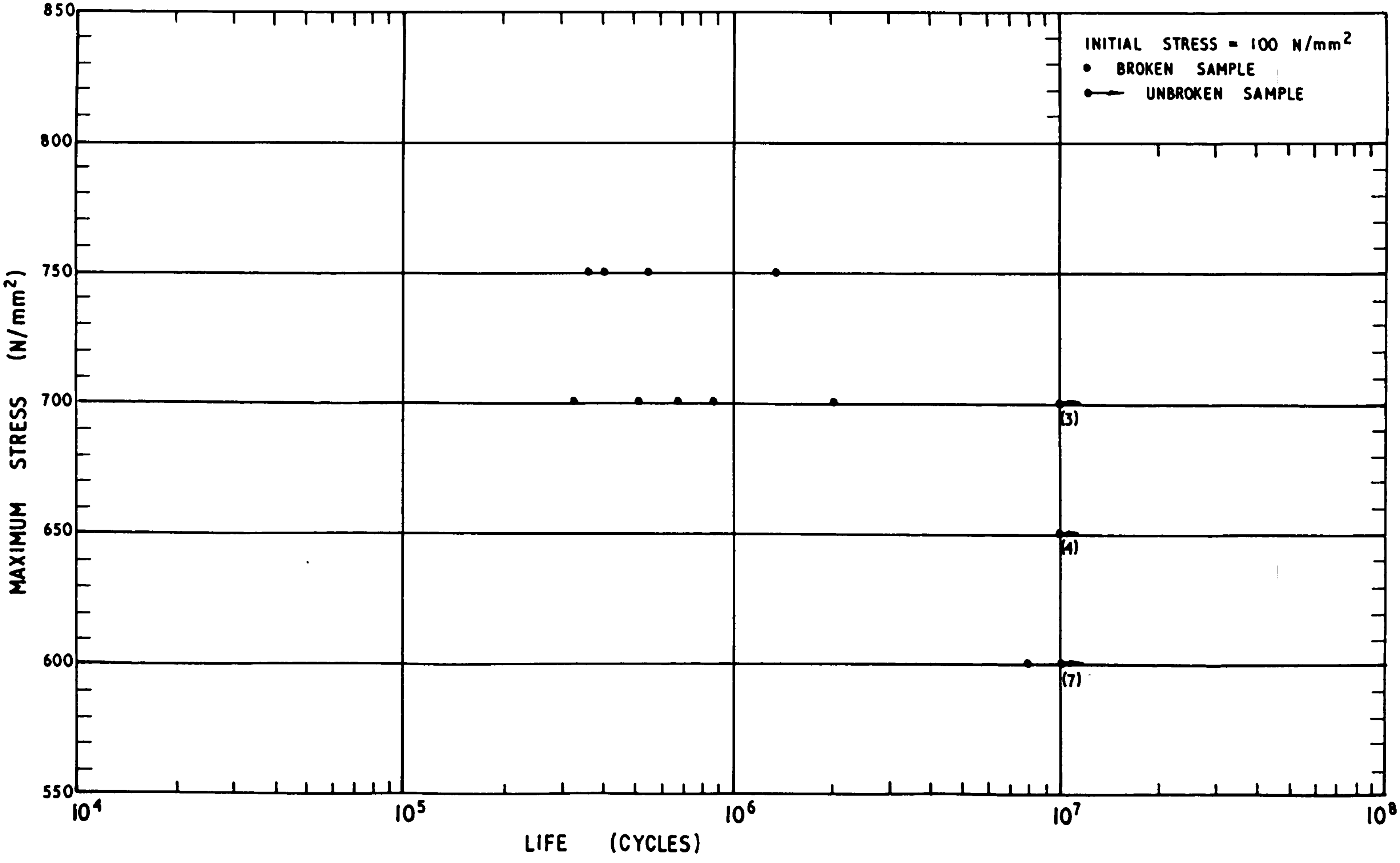


FIG. 8. FATIGUE RESULTS FOR ELECTRO POLISHED SPRINGS MADE FROM BS2056 302S26 WIRE.

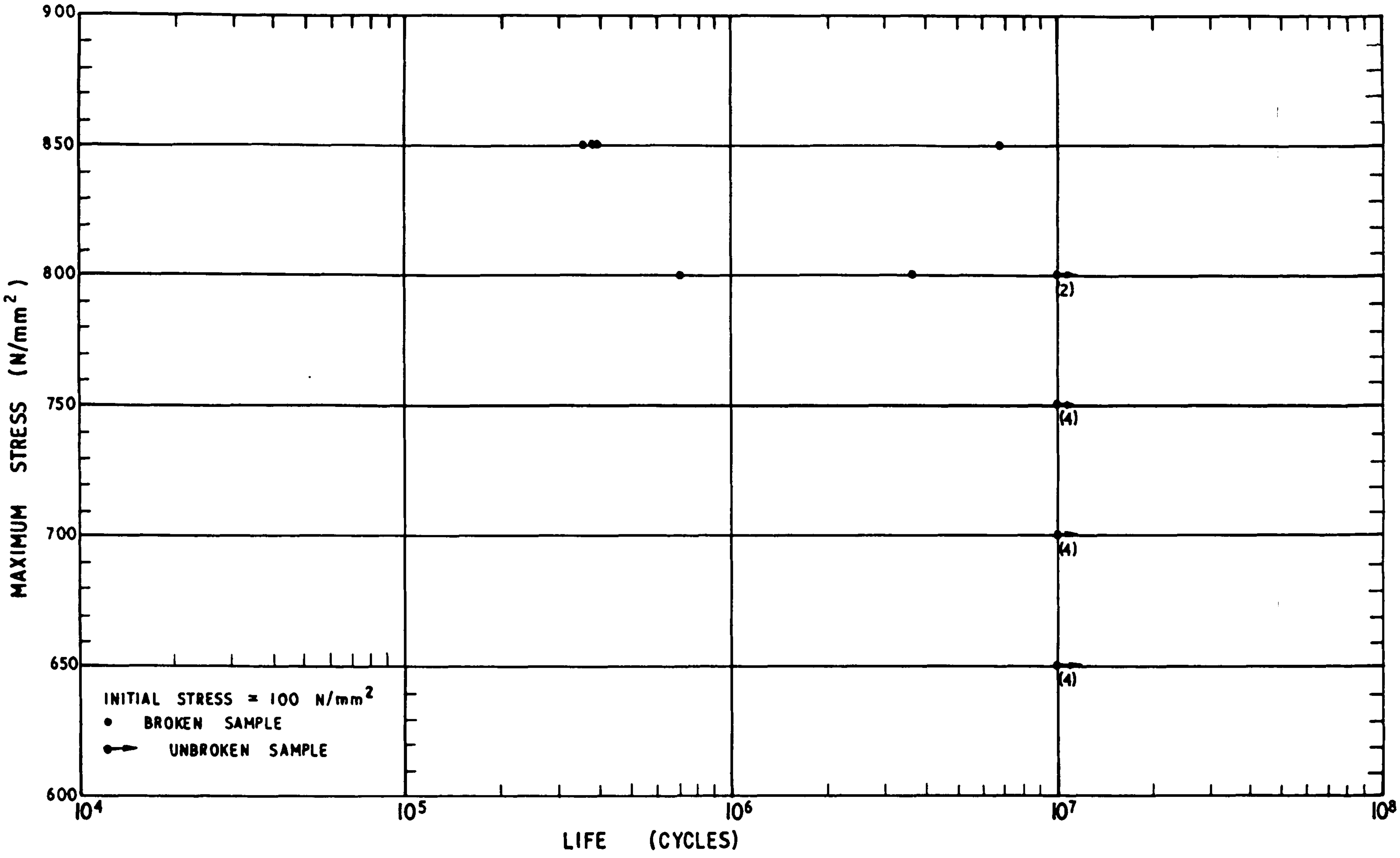


FIG. 9 FATIGUE RESULTS FOR SHOT PEENED SPRINGS MADE FROM BS 2056 302S26 WIRE.

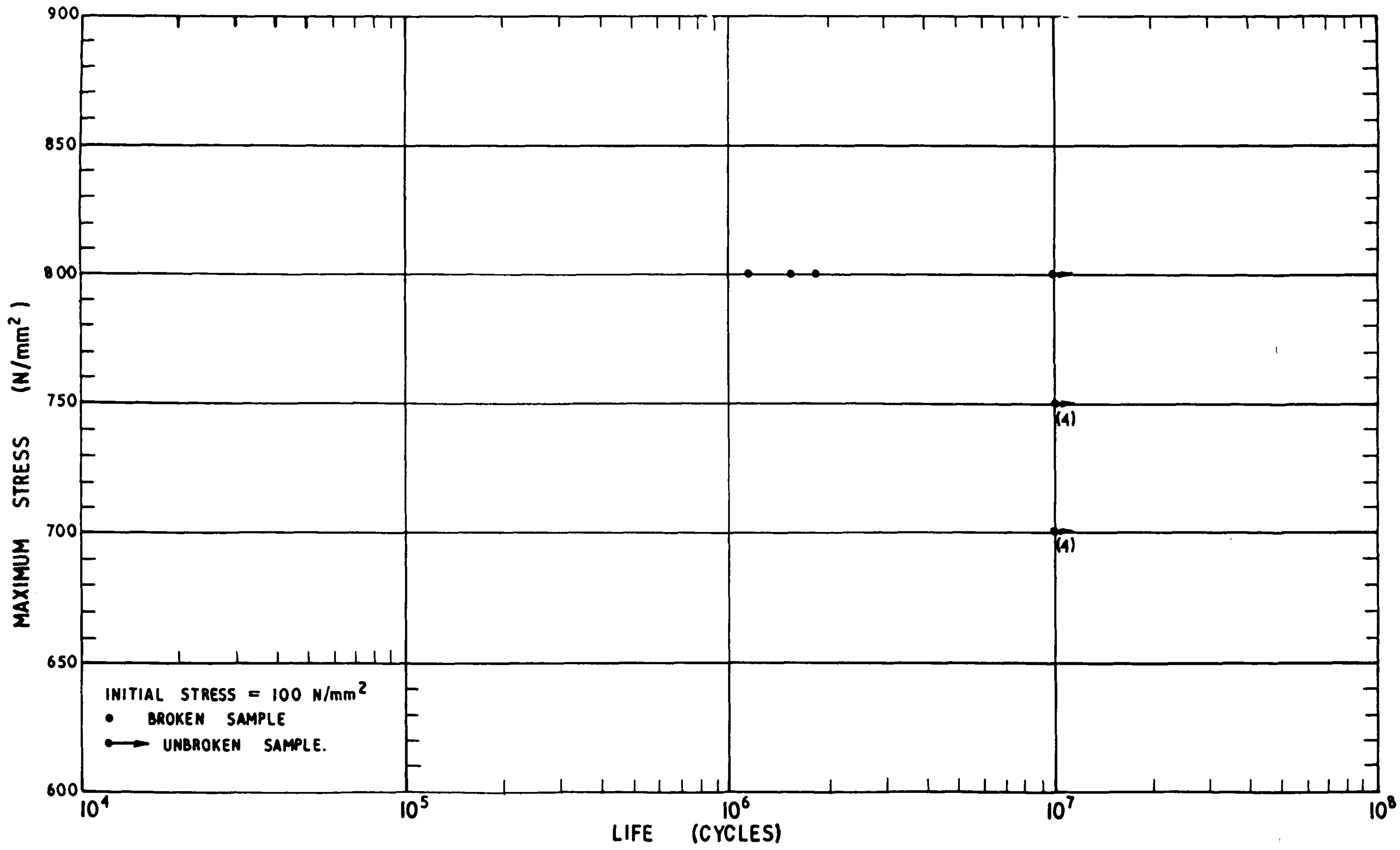
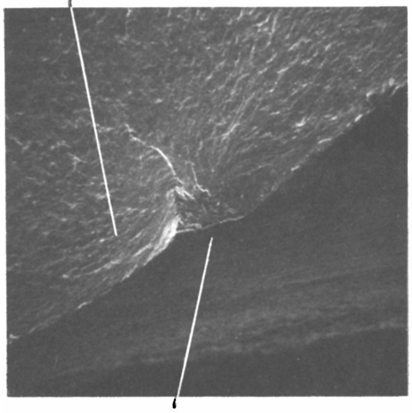


FIG. 10 FATIGUE RESULTS FOR ELECTRO POLISHED AND SHOT PEENED SPRINGS MADE FROM BS 2056 302 S 26 WIRE.

45° tensile crack (stage II)

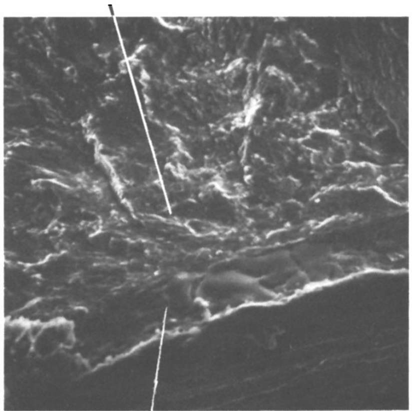


longitudinal shear crack
(stage I)

(i) X66

Fracture initiation zone
showing shear fracture.

shear crack



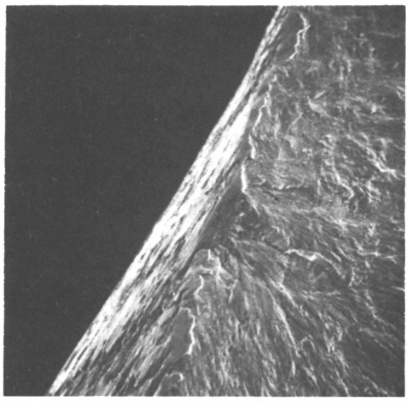
surface roughness

(ii) X660

Details of shear crack to
show surface roughness zone.

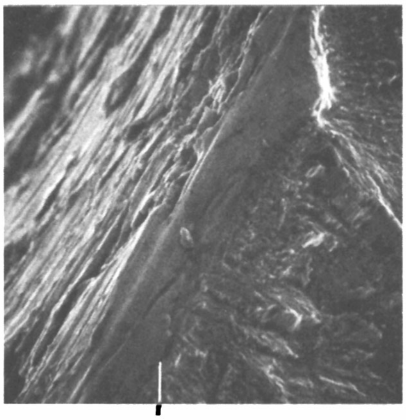
Fig 11

Typical fatigue fracture
initiation for springs of
good surface quality



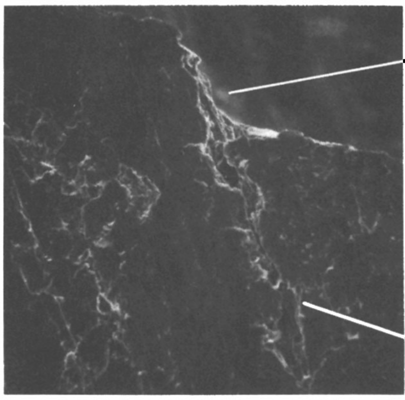
(i) X120

Fracture initiation.



(ii) X600

As above but high magnification.

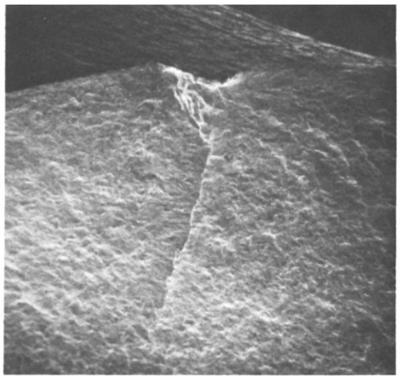


(iii) X120

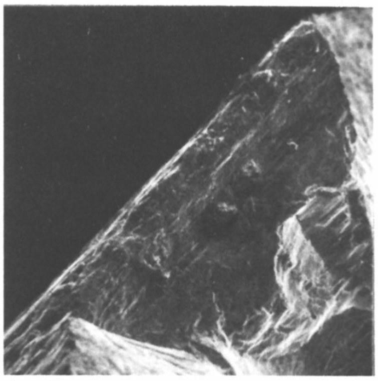
Sample reorientated to show surface roughness associated with stage I shear crack.

Fig 12

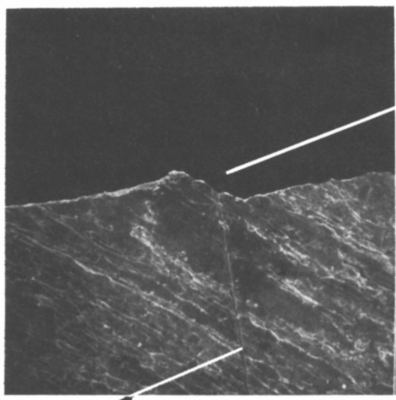
Typical fatigue fracture initiation for springs of average surface quality



(i) X33
Fracture initiation.



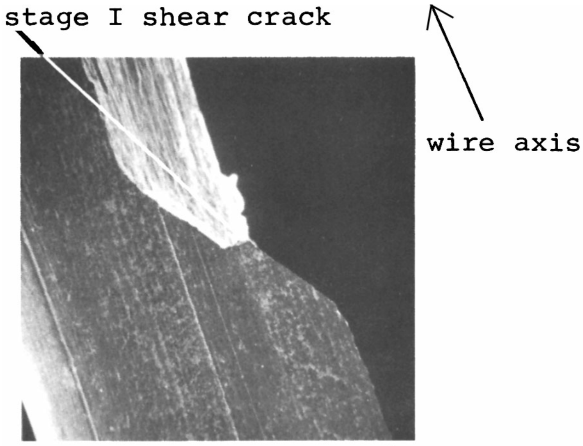
(ii) X120
Detail of stage I shear crack.



(iii) X60
Sample reorientated to show wire axis and 45^{o} cracking in both tensile directions.

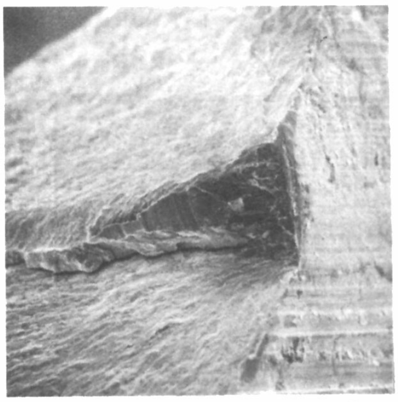
Fig 13

Typical fatigue fracture initiation for springs of poor surface quality



(i) X20

Sample orientated to show wire surface.

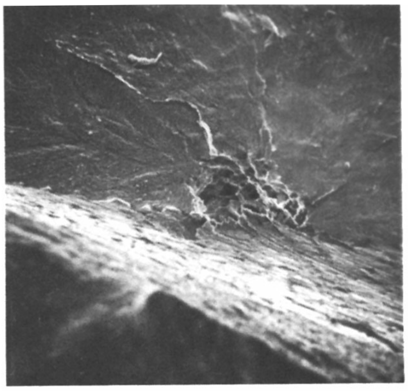


(ii) X150

Sample reorientated to show fracture surface.

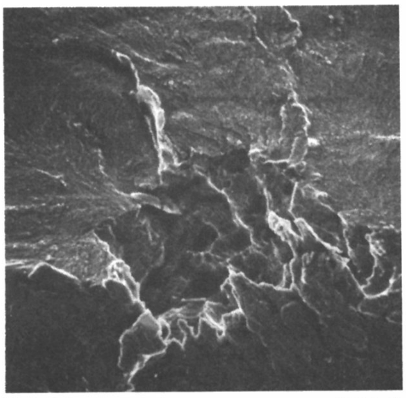
Fig 14

Fatigue fracture of spring made from good surface quality wire with initiation at 90° to wire axis



(i) X130

Wire of average surface quality.



(ii) X315

As above, higher magnification.

Fig 15

Fatigue fractures with initiation at surface pits

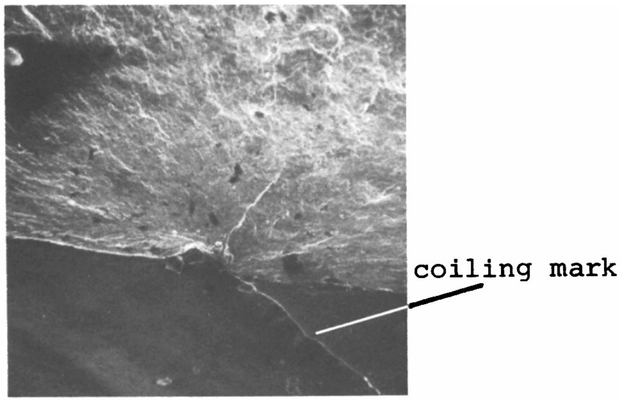


Fig 16 X145

Fatigue fracture of electropolished spring

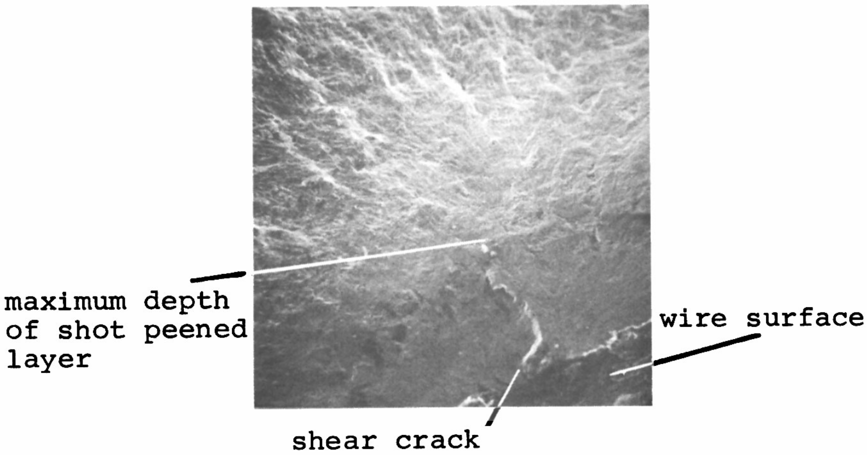


Fig 17 X145

Fatigue fracture of shot peened spring