THE SPRING RESEARCH AND MANUFACTURERS' ASSOCIATION

Decarburisation/Defects and their effect on the dynamic properties of springs made from spring wire.

Report No. 377

by

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FINAL REPORT

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Background

It is well known in general terms that decarburisation and surface defects have an adverse effect on the performance of springs operating under fatigue conditions, and this is recognised to some extent in current spring wire standards.

This simple assertion, and the fact that no technical literature has previously been published to support the limits of decarburisation or surface defects imposed in standards, such as BS 5216, S201, S202, DEF 106 and BS 2803, was the reason for undertaking this systematic programme of work.

The question to be answered was how influential were the various levels of decarburisation and surface defects on the dynamic performance of springs. This question has been answered for springs before and after shot peening.

Introduction

The progress of this programme of work has been reported to the Department of Industry under the following headings.

1. Machine building
2. Wire procurement and confirmatory testing
3. Spring making
4. Fatigue testing
5. Metallographic examination of broken springs
6. Data Analysis

The method of undertaking each section of this work is described in detail using these headings. The results of the work are described under headings 4-6 above. Finally conclusions are drawn and recommendations made for amendment of existing specifications, the provision of a new BSI specification, and for further studies to be undertaken.

Synopsis of Method

The overall programme of work has taken three years to complete. The first fifteen to eighteen months were spent in building a further twelve single station fatigue testing machines similar to the six that SRAMA had already built. At the start of 1983 attempts were made to obtain suitable samples of wire, particularly those showing decarburisation or defects. In all, twenty samples were required, 4 good, 8 showing decarburisation and 8 containing surface defects. Samples were initially sought from wire drawers, but difficulties were experienced in securing small coils of known microstructure from wire drawers and so most wires were eventually taken from springmakers' surplus wire stocks. Obtaining chrome vanadium (735A50) wire with decarburisation and/or defects proved extremely difficult and over 70 samples were examined before selecting coils with comparatively small defect and decarburisation limits compared with the limits selected for each of the other grades of steel.

As soon as a suitable coil of wire had been obtained, confirmatory metallography and chemical analysis was carried out and the coil was sent off for coiling 150 compression springs. Springs were low temperature heat treated to instructions, the ends were ground squarely at SRAMA, and the springs were then load tested. For each batch of 150 springs half were shot peened and stress relieved at SRAMA.

Exploratory fatigue tests were carried out to establish the approximate stress at which half of the springs would survive 10^7 cycles. Fatigue tests were then carried out to enable a probit analysis to be done about this approximate median. By this means the stress at which 99% of the springs would survive 10^7 cycles could be determined. Limited life fatigue tests were also undertaken. These fatigue tests were carried out for unpeened and shot peened springs made from each of the 20 coils of wire obtained. A total of about 2,500 fatigue tests were done during the course of this work.

All fatigue fractures were examined optically. Several springs were sectioned metallographically to confirm the association of defects or decarburisation with fracture. Numerous springs were examined on the scanning electron microscope and the features of fatigue fractures observed in springs were characterised.

The fatigue data was tabulated and analysed. Results were correlated with decarburisation and defect level. The effects of these two aspects of surface quality were clearly defined by the results.

Method

1. Machine Building

Twelve single station fatigue testing machines were built to an established SRAMA design. The machines are electrically driven forced motion machines in which the springs were driven with a pre-set stroke from one pre-set load height. The machines have been built into banks of six and are illustrated by fig. 1.

The programme of work entailed testing approximately 2,500 springs for up to 10 million cycles each. Such a test takes three days to complete, meaning only 12 springs/week could be tested with SRAMA's pre-existing fatigue testing facilities. Hence a further 12 single station fatigue testing machines were made to supplement the six already in existence, thereby enabling the required number of fatigue tests to be completed within 18 months.

2. Wire Procurement and Confirmatory Testing

Twenty coils of wire were required in the size range 2-4mm. These consisted of five coils of hard drawn wire to BS 5216 ND quality and 15 coils of pre-hardened and tempered wire to BS 2803 ND quality, the latter comprising five coils of carbon steel, five coils of CrV quality 735A50 and five coils of SiCr quality 685A55. The five coils of each quality were required so as to represent wire showing two levels of decarburisation, two levels of surface defect and one wire showing neither defect nor decarburisation.

It was originally envisaged that the two levels of decarburisation and defect would be 1.5 and 3% of the wire diameter for each quality. However from initial metallography of a large number of random samples supplied by UK and overseas wire producers it was found that the level of both decarburisation and defect encountered in each grade of steel varied considerably from grade to grade. From the wire producers' samples the following generalisations could be made regarding the likelihood of finding specific levels of decarburisation and defect.

Wire Type	Decarburisation	Defect
BS 5216	Up to 1% frequently seen. Greater depth rarely seen.	Up to 1% occasionally seen - almost always defect associated with decarburisation
BS 2803 Carbon	Up to 1% occasionally seen	Large defects 1% seen more often than in any other grade
BS2803 735A50 Chrome Vanadium	Virtually none seen in over 70 samples examined	Shallow oxidised pits were the worst seen
BS2803 685A55 Silicon Chrome	Some decarburisation seen in almost all samples examined	Defects to 1/2-1% frequently seen

The above findings formed the basis on which small wire coils were selected. In practice it proved difficult to obtain small coils from wire producers because in the two or three days it took for postage of samples and metallography at SRAMA, the coil from which the sample had been taken would be delivered to the customer. In two instances SRAMA members were the customers for coils which were showing features that would be helpful in this project and sample coils were taken at the springmakers' premises. Ten kilogramme coils were requested in each instance.

The majority of coils were obtained from springmakers' surplus wire stocks. It proved relatively easy to visit springmakers, take samples and do metallographic checks at SRAMA in time to request a 10kg coil prior to the wire being used by the springmaker. The identity of surplus wire stocks was not kept as accurately as it should be at some springmakers and four times in the course of this project, confirmatory checks on 10kg coils received at SRAMA proved that the wire had the wrong analysis or wrong microstructure.

On receiving a coil of wire for this project, SRAMA sent one piece away for chemical analysis. One piece was tensile tested (UTS only) in order to check that it conformed to the relevant British Standard. Cross sections and a longitudinal section were taken from each end of the coil to ensure that the defect or decarburisation was present at both ends of the coil. As a result of these confirmatory tests about 50% of the coils received were not used in this project. Full details of the chemical, tensile and metallographic checks made on the coils that were used are contained in tables 1 and 2 together with an explanation of the nomenclature system used throughout for identifying wires.

Photographs of typical decarburisation seen during the project are illustrated in figures 2 and 3. Similar photographs for defects are illustrated in figures 4 and 5.

Spring Procurement and Grinding

Once the 10kg coil had been confirmed as meeting the requirements of the project, springs were ordered. The first three batches of springs were coiled at SRAMA on a Torrington automatic spring coiler. However, most coils of wire were of a size that could not be coiled to spring in-house and so the remaining batches of springs, 150 off each coil of wire, were ordered from member springmakers. The majority were made on a computer controlled hand lathe, which proved to give an accurately produced spring. SRAMA's previous experience with hand coiled springs is that spring to spring variation and inaccuracies in bow and end squareness give a spring that is unsuitable for fatigue testing. The scatter of fatigue results proved to be acceptable for springs made on a computer controlled hand lathe. A few batches of springs were made on an automatic spring coiler.

All 20 batches of springs were ordered to the following parameters:-

No. of coils	5.1/2
No. of active coils	3.1/2
Ends	Closed - to be ground at SRAMA
Free length	Sufficient to enable a solid stress of 1150/1200 N/mm^2
Index	7
Wire size	2-4mm
Quantity	150 off minimum

Using the above parameters a spring was designed for each wire size obtained, and a copy of the design as printed in SRAMA's computer aided spring design checking program was supplied to the maker of the springs. An example of a design sheet is shown in fig 6.

The low temperature heat treatment (LTHT) after spring coiling was specified as follows:-

BS5216	375°C 1/2 hour
BS2803 - all three qualities	400°C 1/2 hour immediately after spring coiling.

A temporary corrosion protective was applied after LTHT and prior to despatch to SRAMA.

A machine was purchased to enable manual grinding of the spring ends at SRAMA, in order that the standard of grinding and control of end squareness could be maintained. The emphasis was placed on control of springmaking in this project in order that spring to spring variation within a batch could be minimised and in this way batch to batch variations could be more clearly revealed.

Half the springs of each batch were shot peened at SRAMA after grinding. A shot size of S330 (.033" diameter cut wire conditioned shot) was used initially, giving an Almen Arc rise of A2 .020" (.50mm) minimum. From metallography of failed springs of 2803 SC SDC type it was suspected that the shot peening was too severe and so for smaller wire sizes of 2.50mm and less S230 shot was subsequently used giving an almen arc rise of A2 .016" (.40mm) minimum. Exposure time in shot peening was standardised at 15 minutes. Metallographic, optical and SEM checks showed that 100% coverage was always achieved in shot peening. Stress relieving after shot peening was carried out at 220°C for 30-60 minutes.

Fatigue Testing

Two sets of fatigue data were required for this project. These data sets were generated to show the effect of decarburisation and defects level on the fatigue limit and separately the effect on the limited life expectancy of more highly stressed springs.

The fatigue limit was determined via a Probit analysis, in which a large number of springs were fatigue tested above and below the fatigue limit of the springs. The Probit technique allows the probability of failure to be established for component operating at particular stress levels.

Limited life tests were performed at a comparatively high stress in order to compare the limited life data of each batch of springs. Both Probit and limited life tests were performed for all 20 batches of springs, both before and after shot peening. Hence forty sets of data were produced and the fatigue test results of every spring tested are shown in graphical form (Figs 7-46).

Fatigue Test Method

Springs, whether shot peened or not were all pre-stressed to solid very thoroughly. This generally meant compressing the spring to solid up to ten times and then checking on a load test, at a length close to solid, that no progressive loss of load occurred.

The outside diameter of each spring was measured, enabling a calculation of the stress in the spring at a given load via the formula:

$$q = \frac{8PDK}{d^3}$$

where q = Corrected torsional stress in spring

P = load

D = mean diameter of spring

K = curvature correction factor = $\frac{c + 0.2}{c - 1}$

$c = D/d$ = spring index

d = wire diameter

In order to establish the fatigue limit and limited life results, the stress at which each spring would be tested was pre-determined and hence the above formula was used to establish a load. Every spring was then load tested on SRAMA's 1000N electronic load tester in order to determine the length at which the spring was supporting the calculated loads. For every fatigue test, a load to give a stress within the spring of $100 N/mm^2$ was used as the lower load in the fatigue test. From the load test results, two lengths would be measured between which the fatigue test would be carried out.

SRAMA's single station forced motion fatigue testing machines were set up using the difference between the two lengths - the stroke on the driving arm initially. With the stroke adjusted the end stop was moved towards the driving arm until it was at the correct distance away from the driving arm at the low load length position, and the end stop was locked into position. All measurements were made using a dial gauge and a vernier rule.

i) Probit Tests

The fatigue tests were carried out to enable a probit analysis of the data according to BS 3518 pt 5:1966. The probit technique permits the evaluation of fatigue stress limit for a given probability of survival.

Initially a stress at which approximately half of the springs survived ten million cycles was established empirically. In practice this stress was generally assumed to be one at which at least one spring broke out of six tested and at least one survived. This stress was not always established correctly on initial tests and sometimes had to be adjusted up or down in the light of further results.

However, once the approximate median stress for 50% survival was established with six springs tested at that stress, then nine springs were tested at one increment of stress higher and lower than the median and twelve springs were tested at two increments of stress higher and lower than the mean. The increments of stress were chosen in such a way that the percentage survival at each stress level most nearly fitted the ideal of the probit distribution which is as follows:

% survival	Relative group size	SRAMA test number
25-75	1	6
80-85	1.5	9
90	2	12

In an ideal test, with the assumed median established precisely three out of six would survive at the assumed median, seven out of nine would survive at the stress one increment above the median and one out of twelve would survive at the stress two increments above the median. Similarly seven out of nine would break at the stress one increment below the median and one out twelve at two increments below. The stress increments that gave results which came nearest to this ideal were 30 N/mm^2 for unpeened springs and 20 to 40 N/mm^2 for shot peened springs.

ii) Limited life data

A stress considerably above the stress for 50% survival to ten million cycles was selected for each material in both the peened and unpeened conditions. Ideally the stress chosen would be one at which the defect free wires gave a life between 2 and 5 x 10^5 cycles. Eight springs were tested at the stress selected in order to illustrate the effect of decarburisation and defect levels on limited life fatigue test results.

Failed Spring Inspection

Each broken spring was examined carefully on a Nachet binocular microscope at magnifications of 4 to 40 times. From these observations springs were further examined on SRAMA's Cambridge S4 Scanning Electron Microscope. In this way the types of failure were characterised and could be recognised on the optical binocular microscope.

From the plot of fatigue test results it was observed that the fatigue life of some springs did not fit the pattern of results normally expected when plotting an S-N curve. For these springs cross sections were taken from behind a fracture surface and the section was mounted, polished and examined metallographically to ensure that no abnormal microstructural problem was associated with premature failure.

A random selection of springs that did fit the normal pattern of fatigue results were also examined metallographically in order to ensure that the decarburisation or defect level was consistent with that observed in the original examination of the wire sample. The results of these examinations are included in table 2.

Synopsis of Results

The wires and details of analysis, tensile strength, decarburisation, and defect level are contained in tables 1 and 2. The springs made from these wires were all made to the general design criteria stated on page 4, except for springs made from BS 2803 Cr$_2$V LDC, for which the solid stress was too low - i.e. 1050 N/mm^2 ordered. For this reason it was not possible to use this batch of springs for the limited life fatigue tests. All other batches of springs were fully tested.

Full details of every load test and fatigue test carried out are not included in this report, but are available for scrutiny at SRAMA. However full details of the results of each fatigue test are presented in graphical form on S-N curves (figs 7-46) in which the life of every spring tested is recorded.

From these fatigue test results probit analyses were performed and a table of results was drawn up on the limited life tests. The technique by which the results of the probit analysis were derived is explained in detail later in this section of the report. However the full details of each probit analysis are not included here, but are also available at SRAMA for scrutiny. Included here is one example of the method employed.

The results of the probit analyses are given in table 3. The results of the limited life data are given in table 4. The effect decarburisation, defect level and shot peening are all clearly illustrated in these tables, which are the basis for the conclusions drawn from this programme of work.

spection of failed springs led to a few results being disregarded. However the main result of the failed spring inspection was that the types of fatigue failures in springs were characterised. Only three basic types of failure were observed and the types and condition of the steel in which each was observed was noted. These results formed the subject matter of a brief article published in the 'Metallurgist' in November 1984, and this article is appended to this report - Appendix I.

Probit Tests

A total of 40 probit analyses were performed. A typical set of results from fatigue tests that enable a probit analysis is shown below:-

Steel 2803 CrV SDC shot peened.

Stress(X)	No. Tested	No. Broken	% broken	Std. deviate(Y)	
				Actual	Assumed
1000	12	1	8.33	-1.3852	-1.3852
1040	9	2	22.22	-0.7655	-0..7655
1080	6	5	83.33	0.9661	0.9661
1120	9	9	100	00	1.8808
1160	12	12	100	00	3.0902

The standard deviate is taken from statistical tables of the normal probability function. The stress (X) is then plotted against standard deviate (U) and a straight line should result. For the results shown above a straight line does not result due to no springs surviving at the top two stresses. In order to enable the analysis it was assumed that one in thirty springs would survive if there were none in nine for the stress one increment above the median and that one in one hundred springs would survive if there were no survivors in twelve at two increments of stress above the median, except in the case illustrated. When no survivors exist at either increment above the median, one in thirty survivors are assumed at the first increment and one in one hundred at the second increment. These assumptions were made equally in the event of no survivors or no breakages at a particular stress. The assumptions are necessary because for some springs the distribution of results about the median is not normal, which is necessary for the Probit analysis. The assumptions are an artificial reduction of the skew in the distribution apparent from the limited number of tests carried out in this project. There is good evidence to support the assumptions made both from theoretical statistics and from observations of the results of tests outside the range of the Probit analysis.

When the straight line has been plotted, the equation of the line can be calculated in the form $Y = a+bX$, the correlation and level of significance of the straight line tested by a students 't' test and finally the stress at which 50% survivors, 95% survivors and 99% survivors, which can be expected on a fatigue test, can be read off.

For the illustrated example 2803 CrV SDC shot peened the equation of the line is:-

$$\text{Std Deviate } (Y) = -30.555(A) + 0.0290(B)\text{x stress } (X)$$

The correlation coefficient for this straight line is 0.992348. The students 'T' of 13.9, with three degrees of freedom, is significant at the 1% level. The stress at which a given percentage of springs will survive can be found by inserting the relevant figure for Y and calculating X. For 50% survival, $Y=0$ and so $X = A/B$ which is 1054 N/mm^2 in this instance.

The full results with all statistical constants, correlations and significance levels are included in table 3.

Limited Life Tests

In limited life fatigue tests it would be expected that the spread of fatigue test results would be much less than the spread of results close to the fatigue limit. In practice however the spread of results proved considerable even when a stress for mean life of 200-500 thousand cycles was aimed for. In the light of the spread of results found on initial tests, a stress was selected at which a comparison could be made between grades as well as within a particular steel grade whenever possible. The results are given in table 4.

As indicated on the note at the bottom of the table of results, the mean life of broken springs was not an accurate guide to the likely usefulness of each wire for manufacture of springs required for limited life operation. However the lowest life recorded at the applied stress is a useful figure and does generally illustrate the performance.

Accuracy and Errors in Fatigue Testing

The stress at which a fatigue test was carried out is subject to some uncertainty. The errors in setting up a typical fatigue test have been estimated as follows:-

Measuring outside diameter of spring +/- 0.5%
Measuring length at a given load +/- 0.25%
Setting stroke on fatigue testing machine +/- 1%
Measuring wire diameter (done on wire coil only and not on each spring) +/- 0.75%

Stress in the spring is proportional to load, outside diameter and proportional to the reciprocal of the wire diameter cubed. Hence the estimate of the greatest error in stress in setting up a fatigue test is approximately +/- 4%. This estimate of error assumes that the spring is perfectly square and exhibits no bow.

Inspection of Failed Springs

The purpose of inspection of failures was to ensure the validity of the fatigue results for each wire, and also to learn more about the characteristics of fatigue failures so that diagnosis of premature failures might be made more accurately in the future.

Metallographic checks revealed that the results for 2803 SiC LDC are not strictly valid. It was found that the microstructure of some springs contained a little ferrite throughout the cross section and these springs were appreciably softer than the original wire sample examined. This variable microstructure may have exaggerated the deleterious effect of the considerable decarburisation in this wire.

Metallographic checks on shot peened springs of 2803C SDC revealed that the physical deformation of the wire surface was excessive when 330 shot was used. This led to a limited number of tests to be carried out on these springs shot peened with 230 shot. The fatigue life was improved when using the smaller shot.

The full results of metallographic checks on springs are summarised in table 2, but the above two cases are the only ones for which invalid resuslts are suggested.

Individual results from some sets of data were found to be invalid on optical inspection of the broken springs. If springs failed due to coil to coil clashing, which led to fretting fatigue, or if the end coil fractured due to the end coil not being inactive (as it was designed to be), then these results were deleted. These invalid results generally occurred in shot peened springs that were stressed too close to the solid stress of the spring. There were no more than 20 such results rejected in the whole programme of work.

The main reason for examining the failed springs was to make observations on the characteristics of fracture appearances. BS 5216 springs

invariably broke with a long fibrous appearance. BS 2803 springs

generally broke with a single fracture surface that was oriented between 45 and 90° to the wire axis.

Specific characteristics of the fracture origin were observed. Three distinct types were identified. This is the subject of a seperate article which was published and is appended to this report - Appendix I.

Discussion of Results

1. Obtaining Wire Samples

In order to obtain defective coils of wire for this project, many samples of wire were examined metallographically. Both decarburisation and surface defects were quite frequently seen, but not in all grades of wire. These results cannot be taken as results of a systematic survey of wire quality, but there are some general trends worthy of note.

For instance if a wire is required that exhibits no decarburisation or surface defects, select BS 2803 CrV quality. If low levels of decarburisation are considered important for whatever reason, do not select BS 2803 SiCr quality. The chances of finding a substantial defect, greater than the 1% maximum specified currently in BS 2803 for ND quality, are greatest for BS 2803 carbon steel wire.

2. Results of Probit Analyses

BS 5216

The fatigue limit for 95% survival ($\sigma 95$) was reduced considerably by the presence of both decarburisation and defects. In unpeened springs 1.3-1.7% decarburisation reduced $\sigma 95$ by about $150 N/mm^2$. Similarly 0.8-1.1% defect reduced $\sigma 95$ by about $180 N/mm^2$. In shot peened springs the decarburisation reduced $\sigma 95$ by $125-153 N/mm^2$ and the 0.8% defect reduced $\sigma 95$ by $124 N/mm^2$ whilst the 1.1% defect (2.6% decarb) reduced $\sigma 95$ by $229 N/mm^2$.

It is not clear from these latter results whether the 1.1% defect or the 2.6% decarburisation or the lower hardness was the reason for the poorer performance of LDF compared with the other wires. However, if decarburisation were limited to 1.5% and defects to 1%, there is no reason to suppose that a reliable and predictable performance would result.

BS 2803 C

In unpeened springs, the defect free wire gave the best fatigue limit.

The effect of decarburisation up to 1.0% was to reduce $\sigma95$ by about 100N/mm^2. The effect of the large defects in SDF and LDF wires of this grade was considerable and reduced 95 by 146-175N/mm^2. Overall, the effect of decarburisation and defects in carbon steel was very similar to the effect observed in BS 5216 steel.

After shot peening a different performance was observed. The defect free wire had a very low fatigue limit with only the LDF wire having a lower value. The reason for the relatively poor performance of this defect free wire was extensively investigated, but no metallographic cause was found to explain this result. The oxide cleanness of this steel was comparatively poor, but the total oxygen content of this steel was not remarkably high when compared to other steels. The $\sigma95$ value for each wire of this grade were all within the band 805-876N/mm^2, but it would have been expected from a limited number of results that if the correct shot had been used on the SDC springs, then $\sigma95$ for this wire would have been in excess of 900N/mm^2.

BS 2803 CrV

No clear correlation of fatigue limit with either decarburisation or defects could be established for this grade, other than the suspicion that small defects might be more detrimental than small amounts of decarburisation. This applies both before and after shot peening. The only clear outcome from these tests was that the LDF wire which exhibited intergranular oxide gave a generally poorer performance.

It should be noted that the defect and decarburisation levels in these wires were very small and so perhaps the results are not surprising. There is nonetheless a spread of 120N/mm^2 on the $\sigma95$ for unpeened springs and 100N/mm^2 for shot peened springs. However the best performance unpeened was certainly not the best performance after shot peening. This must suggest that other metallurgical and physical factors influenced the fatigue limit more than either of small amounts of decarburisation or defects.

BS 2803 SiC

The LDC wire had a variable microstructure and hardness and so the results are not strictly relevant. Nonetheless the performance unpeened is satisfactory, but the relatively low result after shot peening can clearly be attributable to both the excessive decarburisation and variable microstructure.

Disregarding the LDC result, it would appear that small amounts of decarburisation and surface defect have a large detrimental effect in unpeened springs. However, after shot peening the decarburisation and defects would appear beneficial! No logical explanation of these strange results was found. It was observed that the defect free springs failed predominantly from the surface, that the LDF springs failed predominantly from the defect, and the other two SDC and SDF springs failed from sub-surface inclusions. These differences do not seem to point to any conclusion except the possibility that the shot peening on the defect free springs was not as effective as on the other springs. No metallographic evidence was found to support this suggestion.

3. Results of Limited Life Tests

In considering the results of the limited life tests it is probably the lowest fatigue value recorded for each wire that is most important, rather than the mean life, since the lowest value is the one that will be used by spring designers.

BS 5216

The effect of both decarburisation and defects is considerable in reducing the limited life fatigue values of this grade both before and after peening. The effect of defects was slightly greater than that for decarburisation, but the general comments made under the discussion of probit results apply equally well here.

BS 2803C

Again the limited life performance is a replica of the probit results. The result of the defect free shot peened springs is very poor. The effect of the large defect in LDF springs is not as great as would have been anticipated for such a large defect both before and after peening.

BS 2803 CrV

No correlation of performance with any decarburisation or defect levels was observed for this grade.

BS 2803 SiC

The probit results were again replicated, and no further discussion is necessary.

Examination of Failed Springs

Correlation of failure mode with decarburisation and surface defects was not clear cut. Some fatigue fractures were clearly associated with a surface defect (see fig 47) but many springs failed with no evidence of the fracture origin being associated with a defect which was known to be present in the wire. Similarly failures that fell outside the scatter band of results were investigated to see if the decarburisation or defect was greater in that spring than in the original wire. It was found that no metallographic abnormality existed in any early failures, whilst decarburisation and defect levels were generally typical of the original wire.

There is considerable evidence here that other metallurgical and physical parameters influence the fatigue properties of springs. Decarburisation and surface defects do play a role in limiting the fatigue life of BS 5216 springs, and in unpeened wires. However, after shot peening the influence of decarburisation and defects is less than that of other parameters for

BS 2803 wires.

5. Grade Selection/Shot Peening

From the probit results there is clear advice on material selection for dynamic application springs.

First and foremost it is clear that shot peening improves the fatigue limit of springs very considerably. For every wire, the shot peened springs gave a better performance than the unpeened springs. The improvement in 95 for defect free BS 2803C was only 82N/mm^2 and the reason for the small value of this improvement has not been explained. For all other wires the improvement was in the range 145-520N/mm^2. Optimisation of the shot peening process might enhance this improvement still further.

If springs for dynamic applications are not shot peened for any reason there is good reason for selecting BS 2803 CrV wire because of its low incidence of decarburisation and surface defects. However, good quality BS 5216 wire is cheaper and may perform as well.

For shot peened springs BS 2803C did not give a better performance than BS 5216 and since BS 2803C is slightly more expensive, BS 5216 will surely be preferred. BS 2803 CrV and SiC grades gave a substantially improved fatigue performance when springs in these grades were shot peened. It appears that SiC grade, which if purchased to ND quality is slightly cheaper than CrV, does give a slightly better performance and may be preferred for this reason. However the shot peening must be correctly done to mask the effect of almost inevitable decarburisation and surface defects in SiC quality.

There is some evidence that purchase of the more expensive HD grades of BS 2803 steels is probably not worthwhile, since no improvement in performance will be gained if defects or decarburisation are absent.

Conclusions

1. Shot peening of BS 2803 wire springs has a greater influence on fatigue performance than the levels of decarburisation and/or surface defects tested.

2. Shot peening of BS 5216 wire springs will improve fatigue performance to a level unobtainable from unpeened springs.

3. The decarburisation level that should be specified in BS 2803, BS 5216, S201, S202, and DEF 106 is recommended to be 1.5% maximum.

4. Surface defects generally had a greater effect than decarburisation and so the maximum level specified in BS 2803, BS 5216, S201. S202, and DEF 106 should be restricted to 1% maximum.

5. The characteristic appearances of the fatigue fractures in springs have been established.

5. Recommendations

1. A British Standard specification for the shot peening of springs is needed.

2. Further research on the optimisation of shot peening should be carried out to establish the basis for the above new Standard.

3. The effect of defects and decarburisation have been established for wires in the size range 2-4mm diameter. The same approach should be adopted for wire of 10mm diameter since a 1.5% defect at this diameter will be approximately equal to the depth of compressive zone promoted by shot peening i.e. 0.15mm. This may lead to a very different conclusion regarding the efficiency of the shot peening process in masking the effect of decarburisation and/or defects.

TABLE 1

Sheet 1 of 2

ANALYSIS AND TENSILE STRENGTH OF WIRES USED

Wire	C	Si	Mn	P	S	Cr	V	O2	Tensile Strength As received	Tensile Strength After LTHT
5216 OK[3]	.67	.16	.71	.020	.022	-	-	-	1738	1640
5216 SDC	.74	.24	.58	.012	.032	.04	-	-	1824	1775
5216 LDC	.74	.24	.58	.012	.032	.05	-	-	1793	1775
5216 SDF	.78	.27	.72	.020	.012	.01	-	-	1766	1752
5216 LDF	.63	.25	.63	.015	.011	.06	-	-	1631	1575
Specification[1]	.55/.85	.35x	.30/1.00	.030x	.030x	-	-	-	2	-
2803C[4] OK	.62	.24	.75	.017	.015	-	-	.0042	1615	
2803C SDC	.69	.24	.72	.013	.018	.05	-	.0033	1590	
2803C LDC	.62	.20	.77	.012	.014	.03	-	-	1655	
2803C SDF	.61	.23	.76	.027	.023	-	-	-	1640	
2803C LDF	.66	.26	.70	.012	.018	-	-	-	1670	
Specification 1	.55/.75	.30x	.60/1.20	.030x	.030x	-	-	-	2	
2803 CrV[5] OK	.54	.26	.85	.021	.017	.97	.20	-	1653	
2803 CrV SDC	.51	.23	.78	.013	.012	.86	.17	-	1810	
2803 CrV LDC	.52	.20	.76	.009	.017	.92	.16	-	1670	
2803 CrV SDF	.46	.23	.73	.003	.017	.86	.22	-	1705	
2803 CrV LDF	.54	.30	.83	.017	.011	1.01	.20	-	1565	
Specification 1	.46/.54	.10/.35	.60/.90	.035x	.035x	.80/1.10	.15 min	-	2	
2803 SiC[6]OK	.54	1.52	.72	.017	.003	.61	-	.0026	1782	
2803 SiC SDC	.51	1.60	.77	.018	.020	.60	-	.0040	1792	
2803 SiC LDC	.55	1.42	.68	.013	.016	.69	-	.0024	1920	
2803 SiC SDF	.56	1.56	.67	.014	.006	.51	.015	.0050	1742	
2803 SiC LDF	.52	1.40	.68	.007	.017	.64	-	-	1920	
Specification[1]	.50/.60	1.20/1.60	.50/.80	.03x	.025x	.50/.80	-	-	2	

Notes:
1 All analyses are within the checking limits allowable in the relevant specifications.
2 All tensile strength figures are in specification, but for BS5216 wires all conform to ND3 quality except LDF which conforms to ND2. Similarly for BS 2803 SiC quality all wires conform to ND1 except LDC and LDF which conform to ND2 quality.

TABLE 1 (Continued)

Sheet 2 of 2

(3) 5216OK is the nomenclature used to identify defect and decarburisation free BS 5216 wire. For each of the four grades of steel, there are five defect/decarb levels relating. These are:-

OK = No defect No decarburisation
SDC = Small percentage decarburisation
LDC = Large percentage decarburisation
SDF = Small percentage defect
LDF = Large percentage defect

(4) 2803C = BS 2803 carbon steel wire

(5) 2803 CrV = BS 2803 735A50 chrome vanadium steel wire

(6) 2803 SiC = BS 2803 685A95 silicon chromium steel wire

TABLE 2

DEFECT AND DECARBURISATION LEVELS AND METALLOGRAPHY

Wire	Wire diameter mm	As rec'd.	Hardness/Hv10 After LTHT	Maximum decarb depth m/m	%	Max. defect depth m/m	%	Comment on metallography
5216 OK	2.80	467/468	464/473	0	0	0	0	-
5216 SDC	2.95	488/490	498/511	.038	1.3	0	0	4 patches complete decarb to .020mm
5216 LDC	2.95	483/488	488/503	.050	1.7	0	0	4 patches of complete " " .025mm
5216 SDF	3.25	483/488	480/504	.025	0.8	.025	0.8	Defect angular, singular and variable in depth
5216 LDF	2.36	456/462	444/462	.062	2.6	.025	1.1	Patch of complete decarb to .035 mm Many angular defects.
2803 C OK	2.80	466/468	466/468	0	0	0	0	Larger number of small oxide inclusions than usual.
2803 C SDC	2.50	478/480	466/468	.020	0.8	.015	0.6	One patch of partial decarb only
2803 C LDC	2.92	501/501	478/478	.030	1.0	.015	0.5	Complete decarb to .008 mm defects rounded.
2803 C SDF	3.24	491/498	459/468	0	0	.045	1.4	Straight oxidised defect normal to wire surface, consistent depth defect.
2803 C LDF	3.25	503/511	464/464	0	0	.12	3.7	Curved oxidised defect at about 45° to wire surface. Length of defect up to .14mm
2803 CrV OK	3.66	504/506	488/493	0	0	0	0	-
2803 CrV SDC	2.34	539/545	520/542	0.007	0.3	0	0	Slight partial decarb only.
2803 CrV LDC	3.06	500/503	503/508	.013	0.4	0	0	Partial decarb only
2803 CrV SDF	3.66	511/511	475/511	.005	0.1	.021	0.6	Rounded oxidized defects- no per cross section variable 3-6
2803 CrV LDF	4.05	454/459	450/450	.005	0.1	.023	0.6	Oxide penetration around whole section.
2803 SiC OK	3.40	536/542	536/539	0	0	.011	0.3	Small defect found in springs, but not in original wire sample
2803 SiC SDC	3.30	530/536	533/536	.018	0.5	.010	0.3	Patch of complete decarb to .018mm
2803 SiC LDC	3.85	448/572	459/528	.120	3.1	0	0	Inconsistent hardness and micro-structure containing a little ferrite throughout

TABLE 2 (Continued)

DEFECT AND DECARBURISATION LEVELS AND METALLOGRAPHY

Wire	Wire diameter mm	As rec'd	Hardness/Hv10 After LTHT	Maximum decarb depth m/m	%	Max. defect depth m/m	%	Comment on metallography.
2803 SiC SDF	3.80	525/530	500/500	.027	0.7	.025	0.7	Patch of complete decarb found in some springs. Alumina inclusion .016 mm dia.
2803 SiC LDF	3.66	570/579	554/560	.012	0.3	.035	1.0	Numerous oxidised angular defects per section. Isolated alumina inclusion .020 mm diameter.

RESULTS OF PROBIT ANALYSES

TABLE 3

Sheet 1 of 2

BS5216		UNPEENED							SHOT PEENED						
Defect		y = a + bX		Correlat^n Coeff.	Level of Signif.	Fatigue Limit for % survival			Y = a +bX		Correlat^n Coeff.	Level of Signif.	Fatigue Limit for % survival		
		a	b			σ50	σ95	σ99	a	b			σ50	σ95	σ99
2.80	OK	-27.91	0.036	0.98	1%	775	729	710	-22.55	0.021	0.91	5%	1073	995	963
2.95	SDC	-19.70	0.031	0.98	1%	635	582	560	-23.55	0.026	0.99	1%	906	842	816
2.95	LDC	-16.12	0.025	0.90	5%	644	579	552	- 6.44	0.017	0.92	5%	967	870	830
3.25	SDF	-14.83	0.024	0.89	5%	617	549	520	-21.70	0.023	0.96	1%	943	871	842
2.36	LDF	-21.23	0.036	0.99	1%	589	544	525	-15.44	0.018	0.96	5%	857	766	728

BS2803 C		UNPEENED							SHOT PEENED						
Defect		Y = a + bX		Correlat^n Coeff.	Level of Signif.	Fatigue Limit % survival			Y = a+ bX		Correlat^n Coeff.	Level of Signif.	Fatigue Limit for % survival		
		a	b			σ50	σ95	σ99	a	b			σ50	σ95	σ99
	OK	-25.82	0.033	0.95	5%	782	732	712	-15.49	0.017	0.97	1%	911	814	774
	SDC	-16.24	0.021	0.91	5%	773	695	662	-21.11	0.023	0.95	5%	917	846	816
	LDC	- 9.89	0.013	0.89	5%	760	634	581	-18.97	0.020	0.92	5%	948	866	832
	SDF	-14.54	0.022	0.97	1%	660	586	555	-19.18	0.020	0.98	1%	959	876	842
	LDF	-18.36	0.030	0.92	5%	612	557	534	-14.54	0.016	0.95	5%	908	805	763

Minimum stress 100N/mm^2

RESULTS OF PROBIT ANALYSES Table 3 (Continued)

BS 2803 Cr V	UNPEENED							SHOT PEENED						
Defect	Y = a + bX		Correlat^n Coeff.	Level of Signif.	Fatigue Limit % survival			Y = a + bX		Correlat^n Coeff.	Level of Signif.	Fatigue limit for % suvival		
	a	b			σ 50	σ95	σ99	a	b			σ50	σ95	σ99
OK	-24.14	0.032	0.98	1%	754	702	681	-23.52	0.023	0.96	1%	1022	951	921
SDC	-12.81	0.016	0.97	1%	772	673	632	-30.55	0.029	0.99	1%	1054	997	973
LDC	-22.65	0.028	0.99	1%	808	750	725	-21.35	0.022	0.87	5%	970	895	864
SDF	-17.45	0.025	0.90	5%	698	632	604	-30.92	0.030	0.96	1%	1030	975	953
LDF	-21.16	0.029	0.97	1%	717	661	638	-24.39	0.025	0.94	5%	975	909	882

BS 2803 SiC	UNPEENED							SHOT PEENED						
Defect	Y = a + bX		Correlat^n Coeff.	Level of Signif.	Fatigue Limit % survival			Y = a + bX		Correlat^n Coeff.	Level of Signif.	Fatigue Limit for % survival		
	a	b			σ50	σ95	σ99	a	b			σ50	σ95	σ99
OK	-24.14	0.032	0.98	1%	754	702	682	-14.09	0.013	0.94	5%	1083	957	904
SDC	-15.02	0.025	0.99	1%	600	535	507	-36.47	0.033	0.94	5%	1105	1055	1034
LDC	-21.91	0.031	0.95	5%	706	653	632	-19.59	0.020	0.98	1%	979	897	863
SDF	-14.16	0.022	0.92	5%	643	568	537	-23.83	0.022	0.93	5%	1083	1008	971
LDF	-25.06	0.040	0.96	1%	626	585	568	-25.46	0.023	0.95	5%	1106	1035	1005

Minimum stress 100N/mm^2

TABLE 4 LIMITED LIFE FATIGUE TEST RESULTS

1\. BS.5216

Unpeened Stress 840N/mm^2				Shot peened Stress 1080 N/mm^2			
Defect Level	Range of Life	Mean	% survivors	Defect Level	Range of Life	Mean	% survivors
OK	249,010-1,667,980	614,180	0	OK	352,900-7,961,640	2,614,314	0
SDC	198,820- 657,610	381,421	0	SDC	160,660- 401,010	248,004	0
LDC	239,180- 471,910	334,374	0	LDC	187,620- 564,490	335,261	0
SDF	105,820- 227,810	157,830	0	SDF	114,090- 868,870	302,774	0
LDF	196,150- 343,400	256,348	0	LDF	81,030- 782,430	357,871	0

2\. BS.2803 C

Unpeened Stress 840N/mm^2				Shot peened Stress 1040N/mm^2			
Defect Level	Range of Life	Mean	% survivors	Defect Level	Range of Life	Mean	% survivors
OK	630,840-4,893,170	2,250,474	0	OK	66,580-1,285,570	348,811	0
SDC	129,460-10^7	850,400	37.1/2	SDC	110,710-2,080,200	529,597	0
LDC	93,920-10^7	3,625,143	12.1/2	LDC	104,200-4,788,700	1,053,524	0
SDF	83,980- 129,890	108,732	0	SDF	152,180-1,903,250	691,343	0
LDF	102,430- 317,650	168,017	0	LDF	68,070- 152,100	95,023	0

3\. BS 2803 CrV

Unpeened Stress 810 N/mm^2				Shot peened Stress 1100N/mm^2			
Defect Level	Range of Life	Mean	% survivors	Defect Level	Range of Life	Mean	% survivors
OK	274,720-10^7	774,456	12.1/2	OK	163,300- 442,230	323,641	0
SDC	260,440-10^7	385,628	25	SDC	260,170-10^7	493,130	37.1/2
LDC	97,890-10^7	1,142,670	25	LDC	-	-	-
SDF	255,060-10^7	1,241,107	25	SDF	104,470-10^7	307,347	12.1/2
LDF	173,020-2,601,780	679,017	0	LDF	104,950- 278,630	172,592	0

4\. BS 2803 SiC

Unpeened Stress 810N/mm^2				Shot peened Stress 1100N/mm^2			
OK	302,560-2,066,200	769,239	0	OK	246,720-10^7	842,346	37.1/2
SDC	177,590-1,365,260	835,120	0	SDC	2,279,130-10^7	5,168,368	12.1/2
LDC	207,610- 326,570	261,169	0	LDC	218,030-4,205,250	1,334,949	0
SDF	122,000-1,803,500	649,861	0	SDF	1,410,910-6,225,410	4,530,356	0
LDF	103,010- 425,630	214,267	0	LDF	369,950-10^7	2,702,913	62./2

The mean stated in the above table is the average life of the broken springs only, and is generally meaningless where some springs survived, and is often distorted by one long life spring even where all the springs broke.

Minimum stress 100N/mm^2

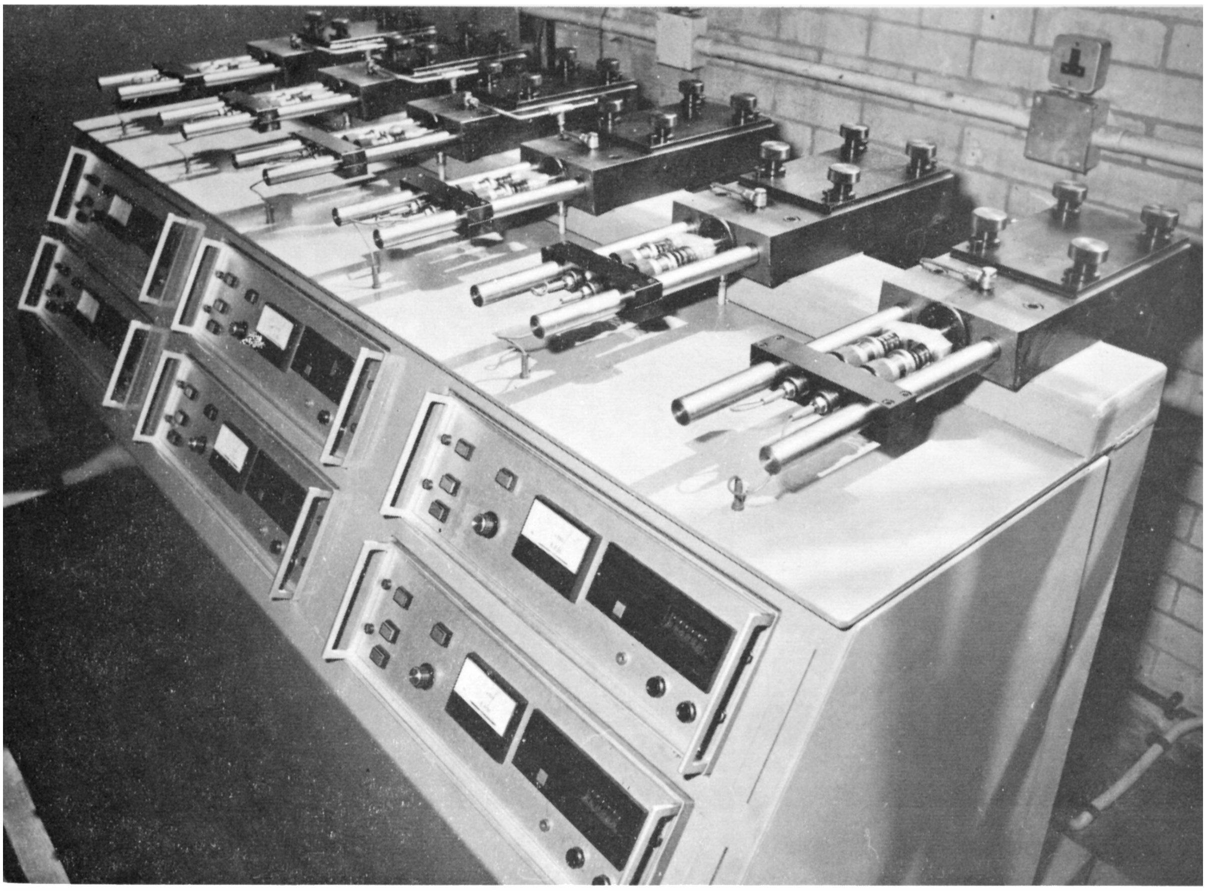

fig 1

Bank of 6 SRAMA fatigue testing machines

Typical Decarburisation Seen

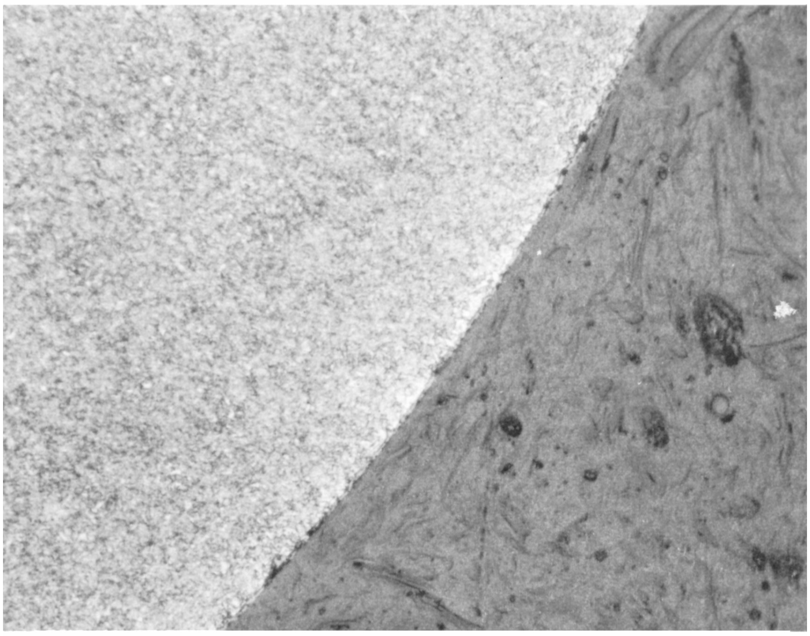

fig 2 x 200

Photomicrograph of BS 2803 SiC SDC wire

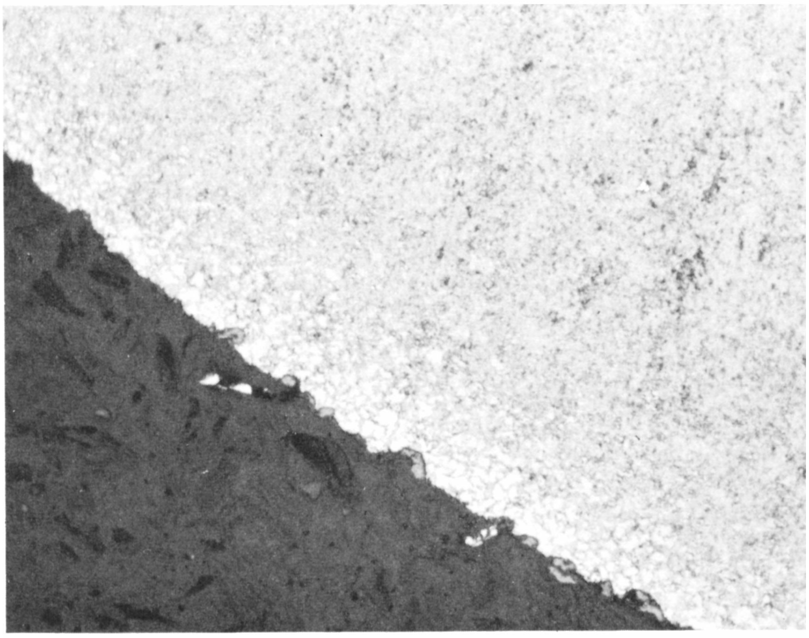

fig 3 x 200

Photomicrograph of BS 2803 SiC LDC

Typical surface defects seen

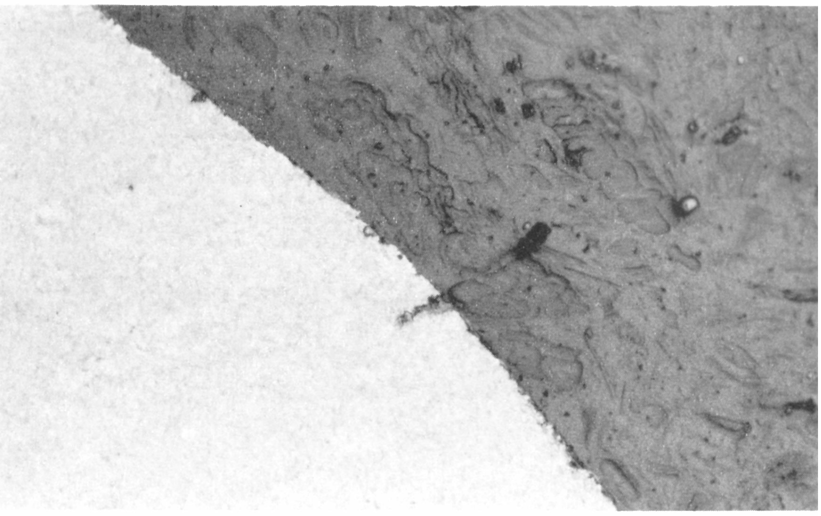

fig 4 x 200
Photomicrograph of BS 2803 C SDF wire

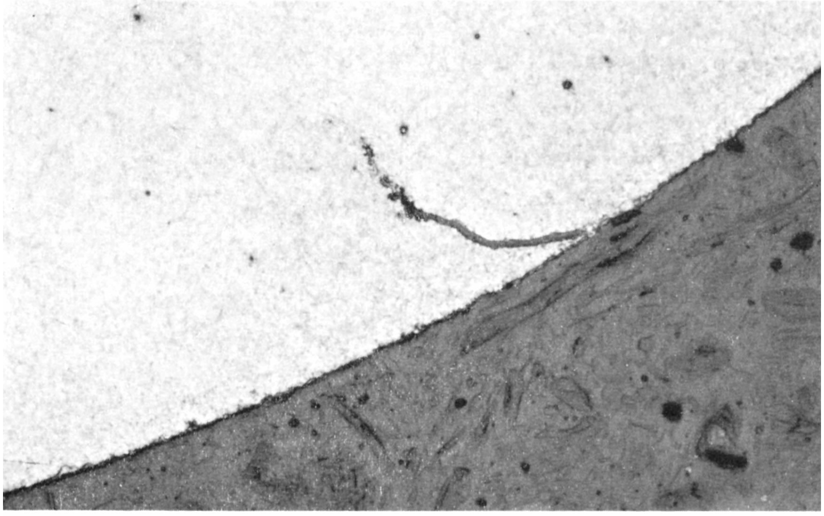

fig 5 x 200
Photomicrograph of BS 2803 C LDF wire

MATERIAL

CARBON STEEL
TORSIONAL MODULUS = 79300 (N/mm^2)
YOUNG'S MODULUS = 206700 (N/mm^2)
DENSITY = 7,83E-06 (kg/mm^3)

SPECIFICATION

WIRE DIAMETER ....= 2.36 (mm)
OUTSIDE DIAMETER ....= 19.5 (mm)
FREE LENGTH ....= 32 (mm)
TOTAL NUMBER OF COILS ....= 5.5
CLOSED & GROUND

HELIX ANGLE ABOVE RECOMMENDED MAXIMUM OF 7.5 (degs)

CALCULATED VALUES

SPRING INDEX ....= 7.26271
WAHL STRESS CORRECTION FACTOR .....= 1.19161
MEAN COIL DIAMETER ....= 17.14 (mm)
INSIDE DIAMETER ....= 14.78 (mm)
HELIX ANGLE ....= 8.23632 (degs)
WIRE LENGTH ....= 298.225 (mm)
WIRE WEIGHT ....= .0102146 (kg)
SPRING RATE ....= 17.4474 (N.mm)
NUMBER OF ACTIVE COILS ....= 3.5
SOLID LENGTH ....= 12.98 (mm)
SOLID LOAD ....= 331.85 (N)
SOLID STRESS ....= 1313.08 (N/mm^2)
NATURAL FREQUENCY ....= 49321.4 (r.p.m.)
SPRING NOT PRONE TO BUCKLING

fig 6

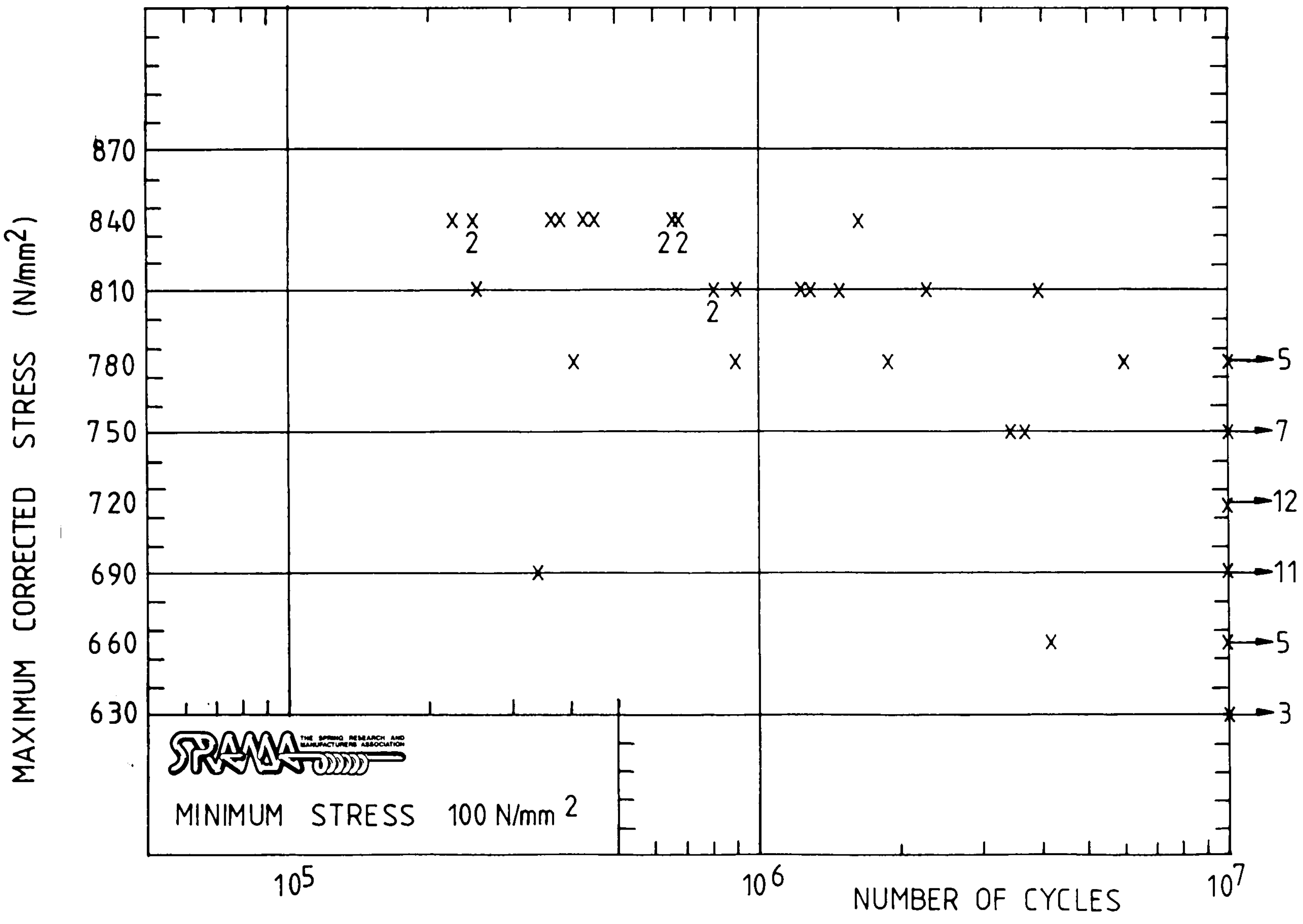

FIG 7. FATIGUE TEST RESULTS: BS 5216 OK UNPEENED.

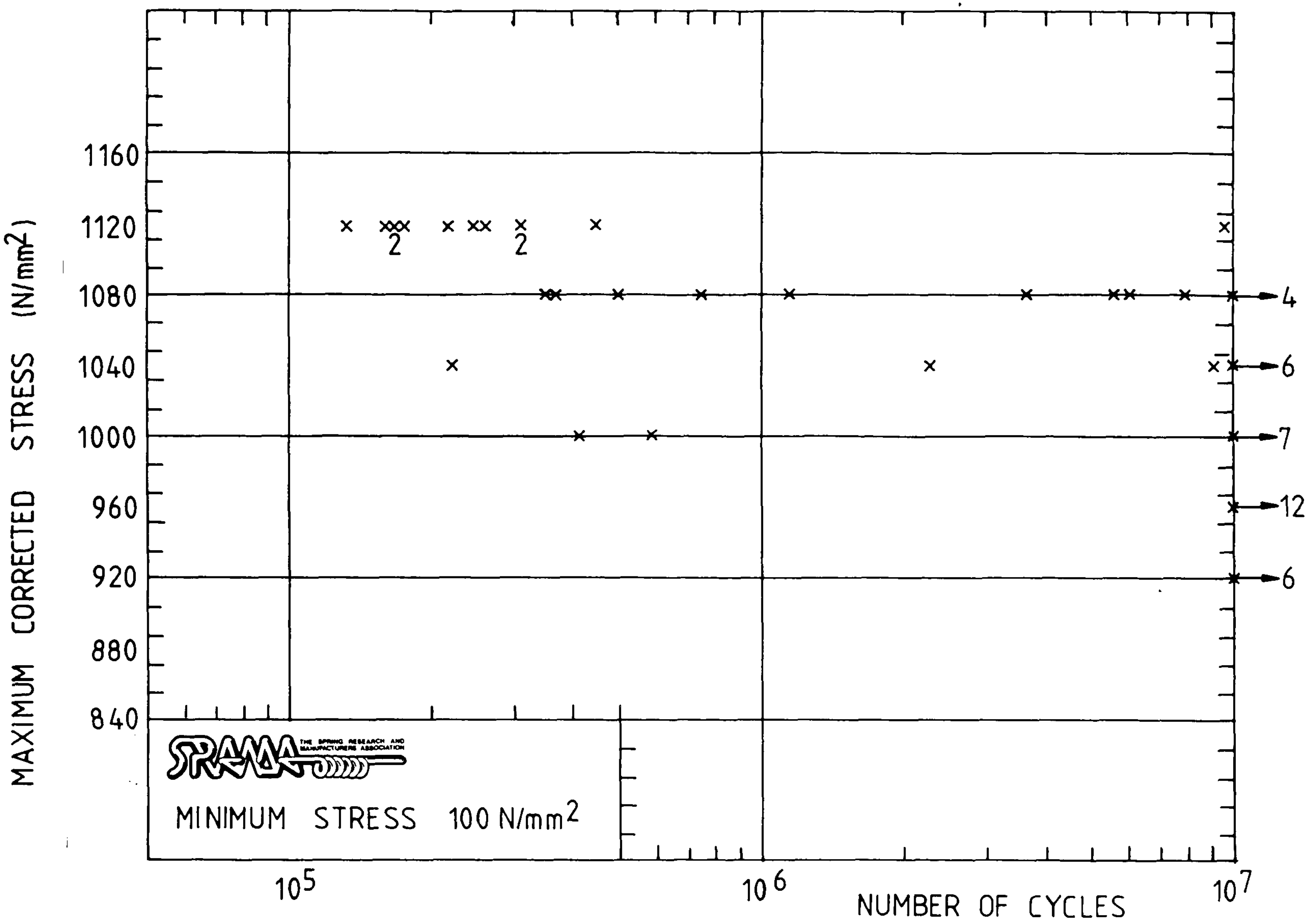

FIG 8. FATIGUE TEST RESULTS: BS 5216 OK SHOTPEENED.

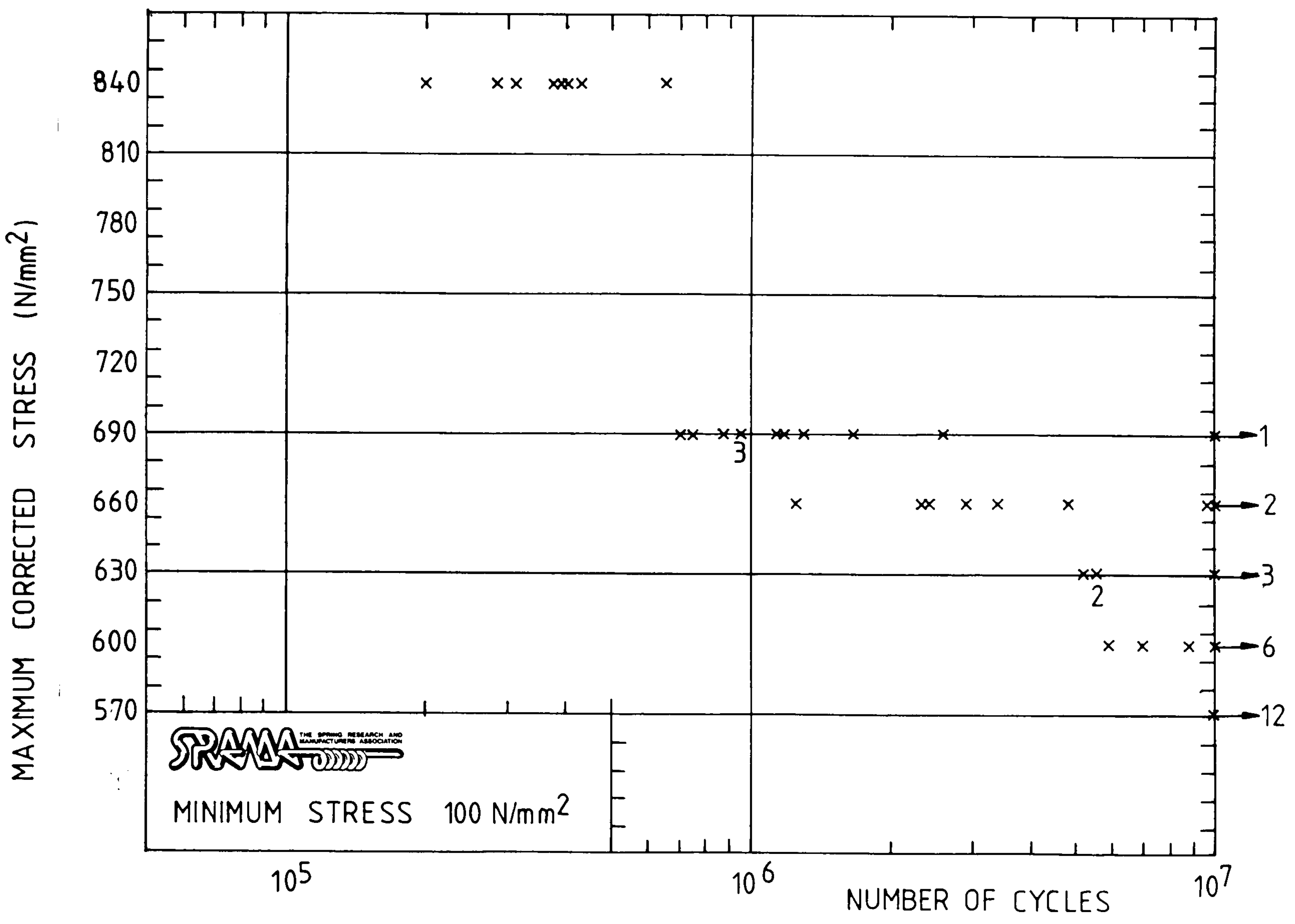

FIG 9. FATIGUE TEST RESULTS: BS 5216 SDC UNPEENED.

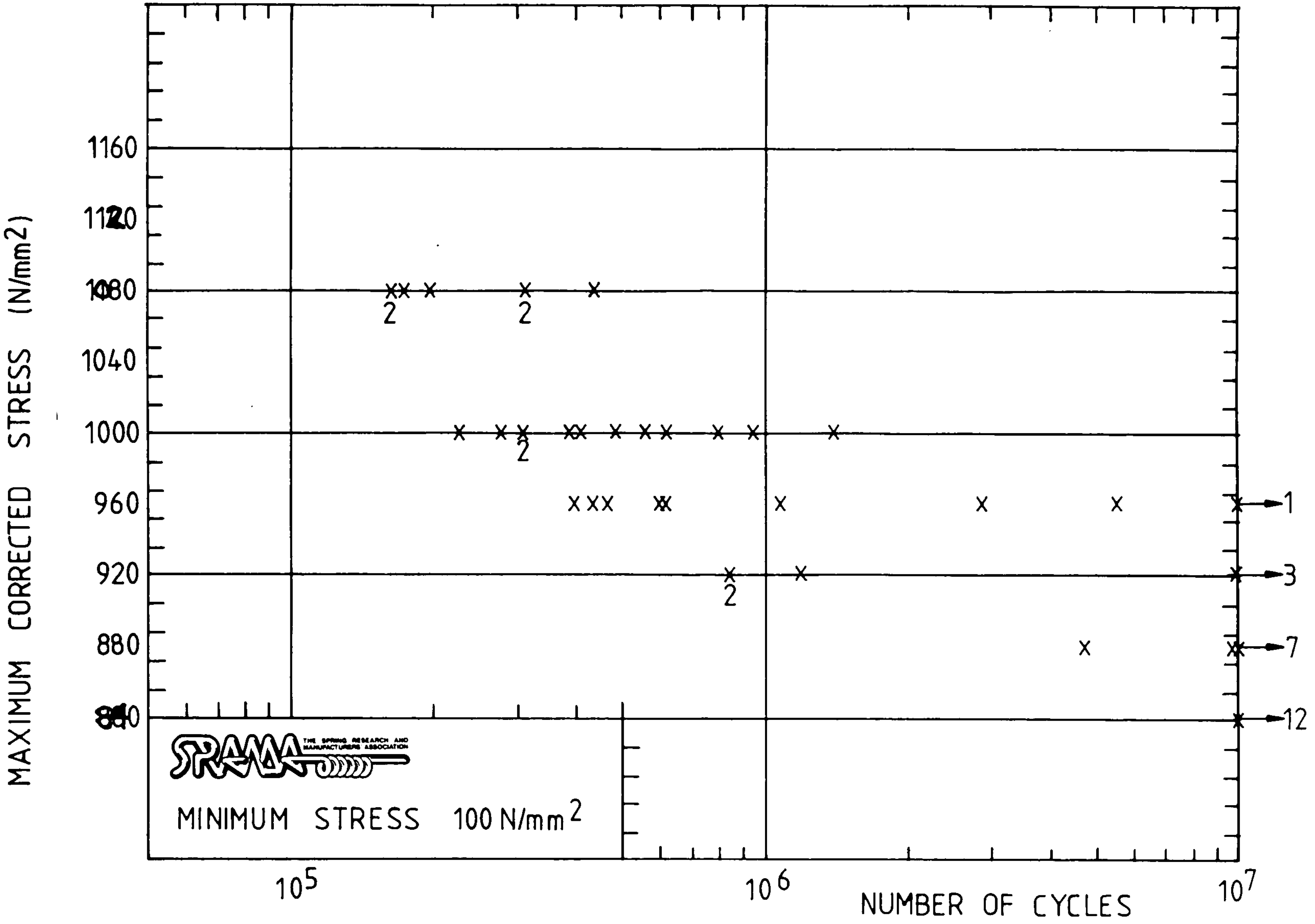

FIG 10. FATIGUE TEST RESULTS: BS 5216 SDC SHOTPEENED.

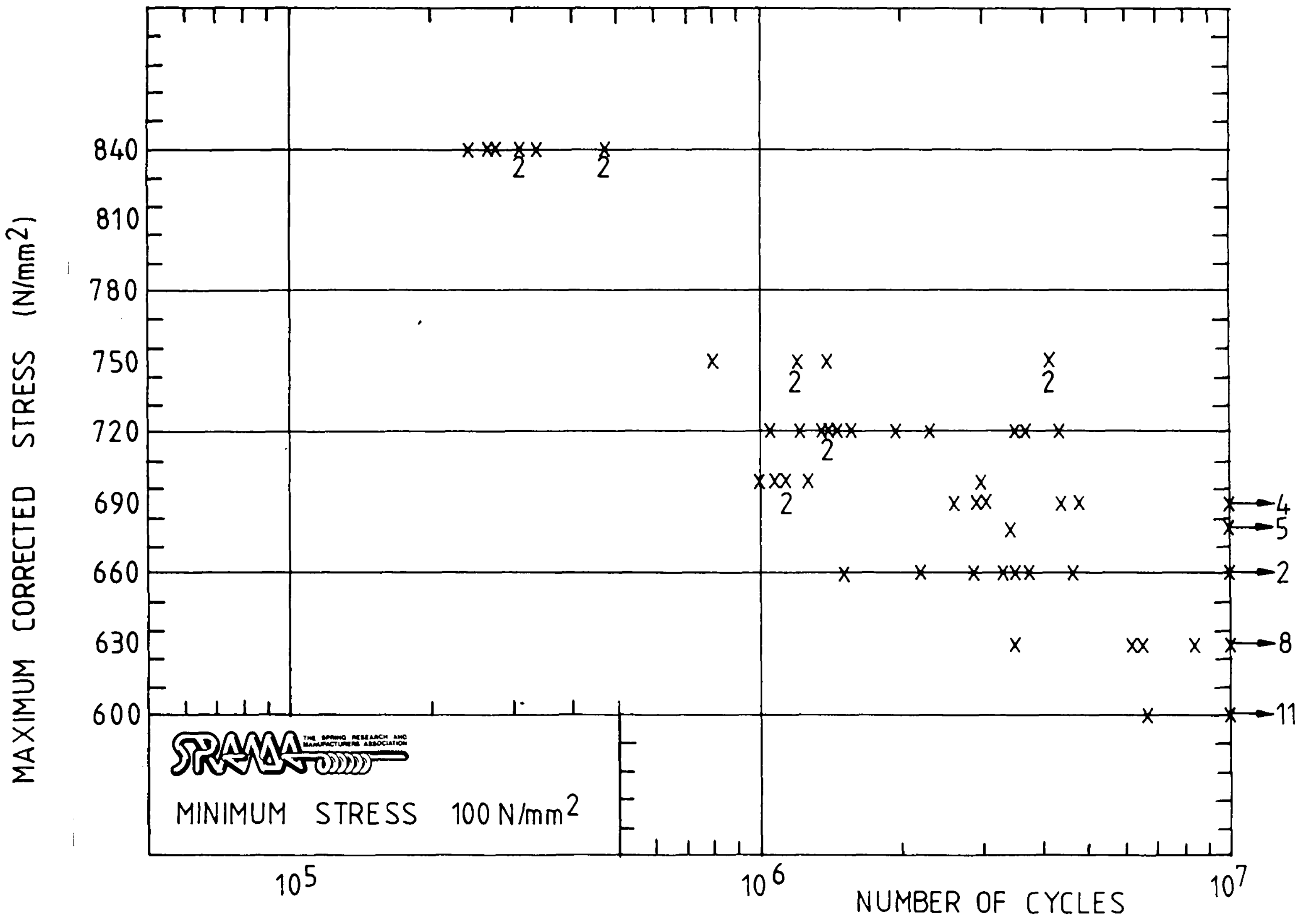

FIG 11. FATIGUE TEST RESULTS: BS 5216 LDC UNPEENED.

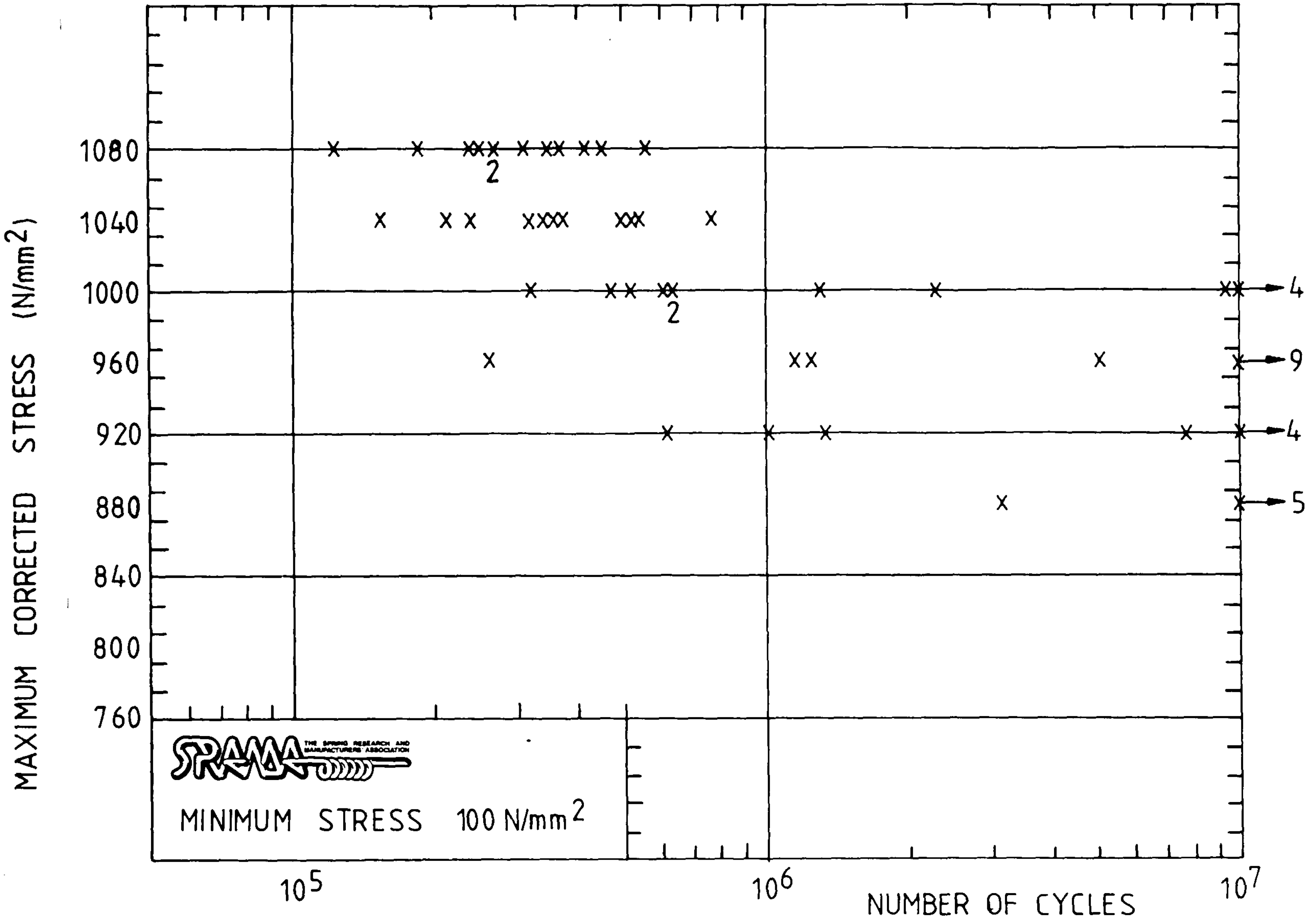

FIG 12. FATIGUE TEST RESULTS: BS 5216 LDC SHOTPEENED.

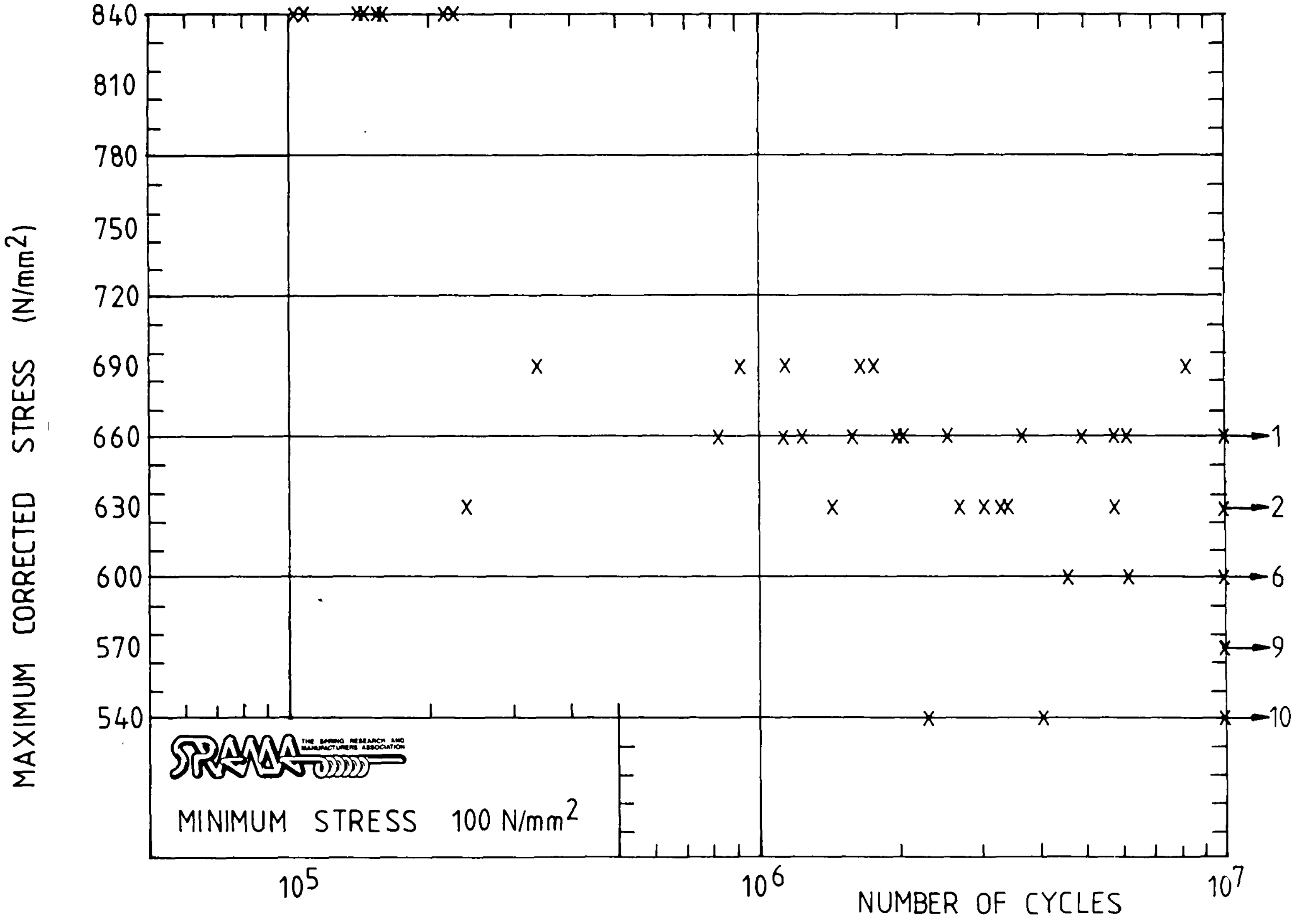

FIG 13. FATIGUE TEST RESULTS: BS 5216 SDF UNPEENED.

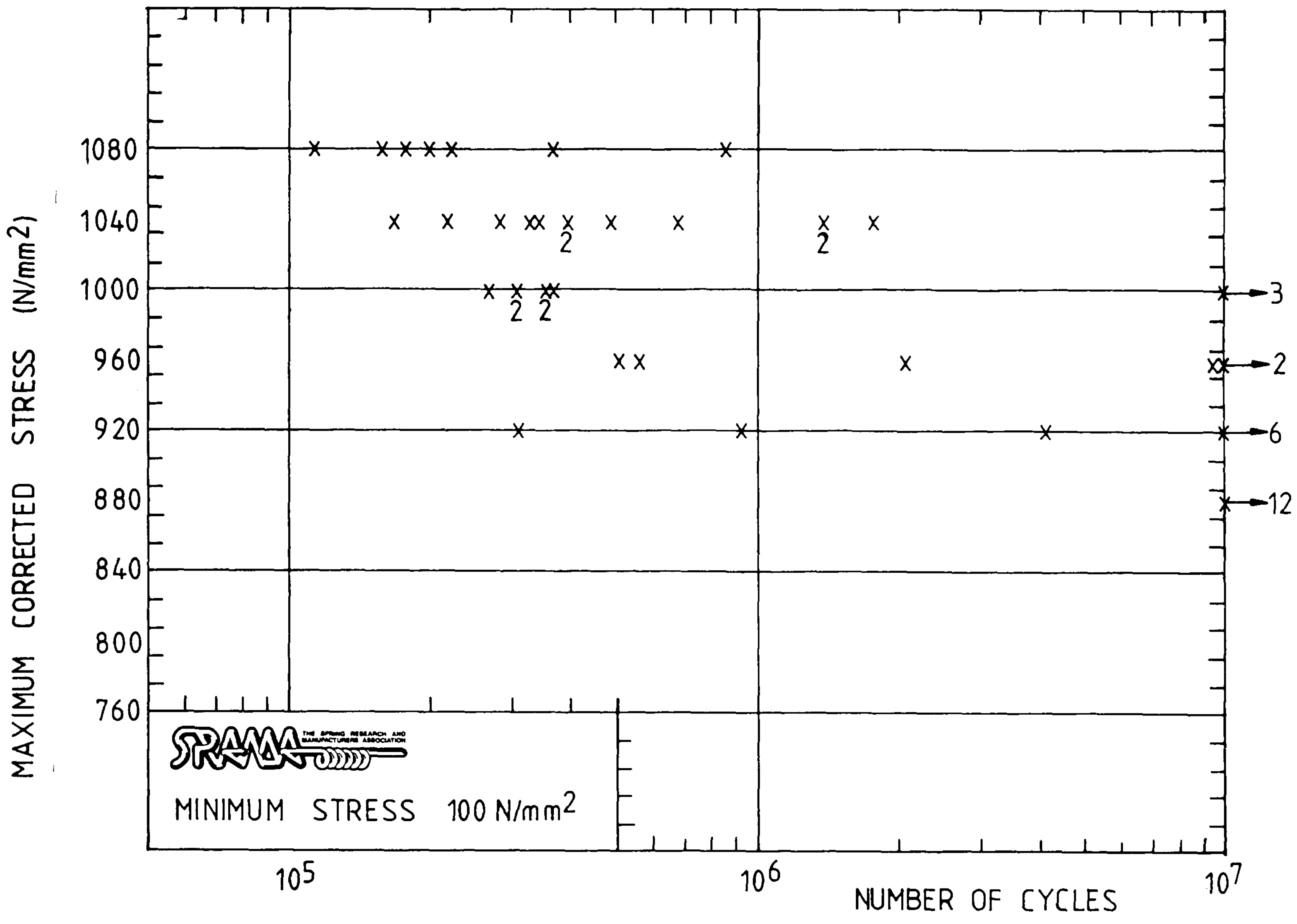

FIG 14. FATIGUE TEST RESULTS: BS 5216 SDF SHOTPEENED.

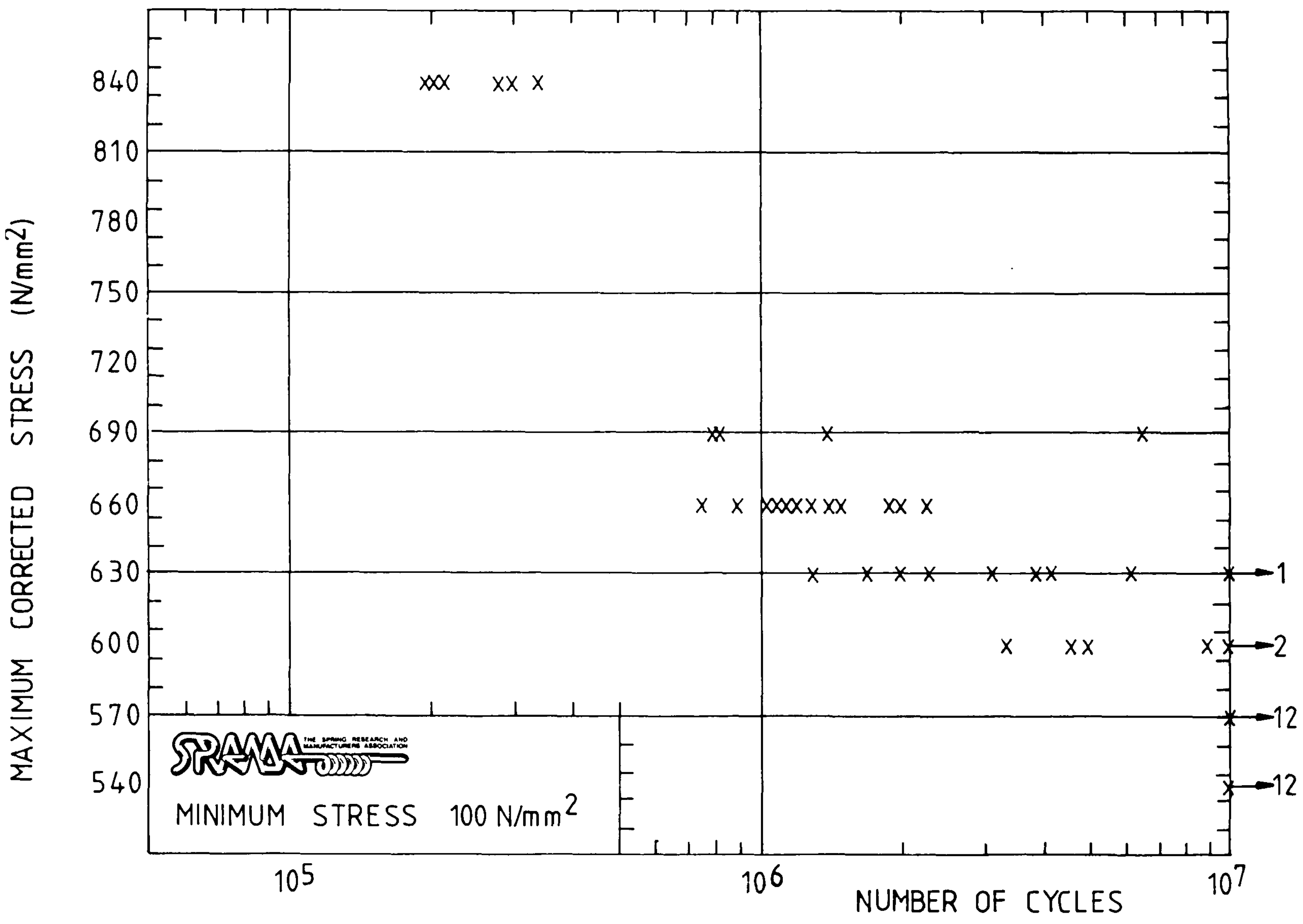

FIG 15. FATIGUE TEST RESULTS: BS 5216 LDF UNPEENED.

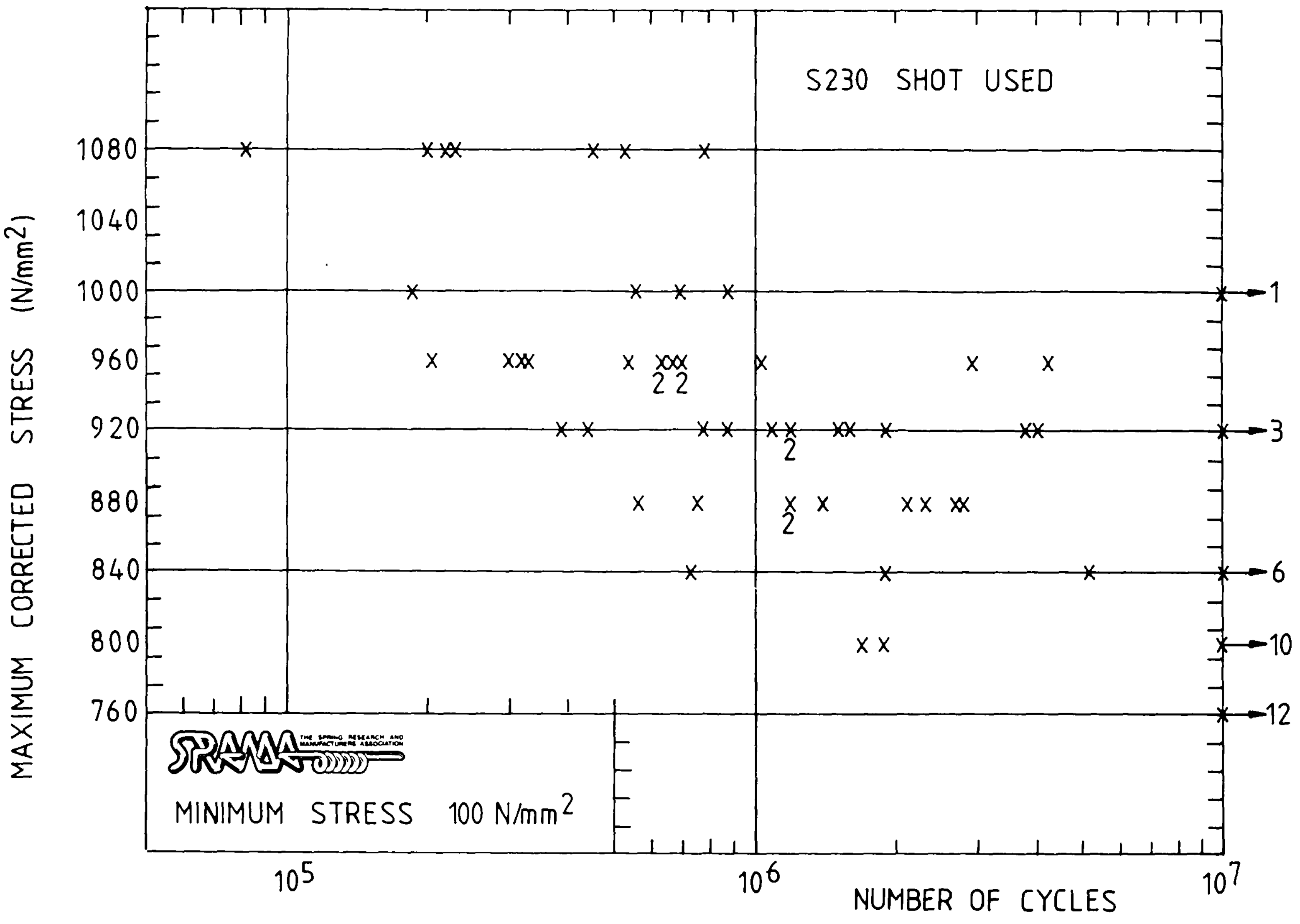

FIG 16. FATIGUE TEST RESULTS: BS 5216 LDF SHOTPEENED.

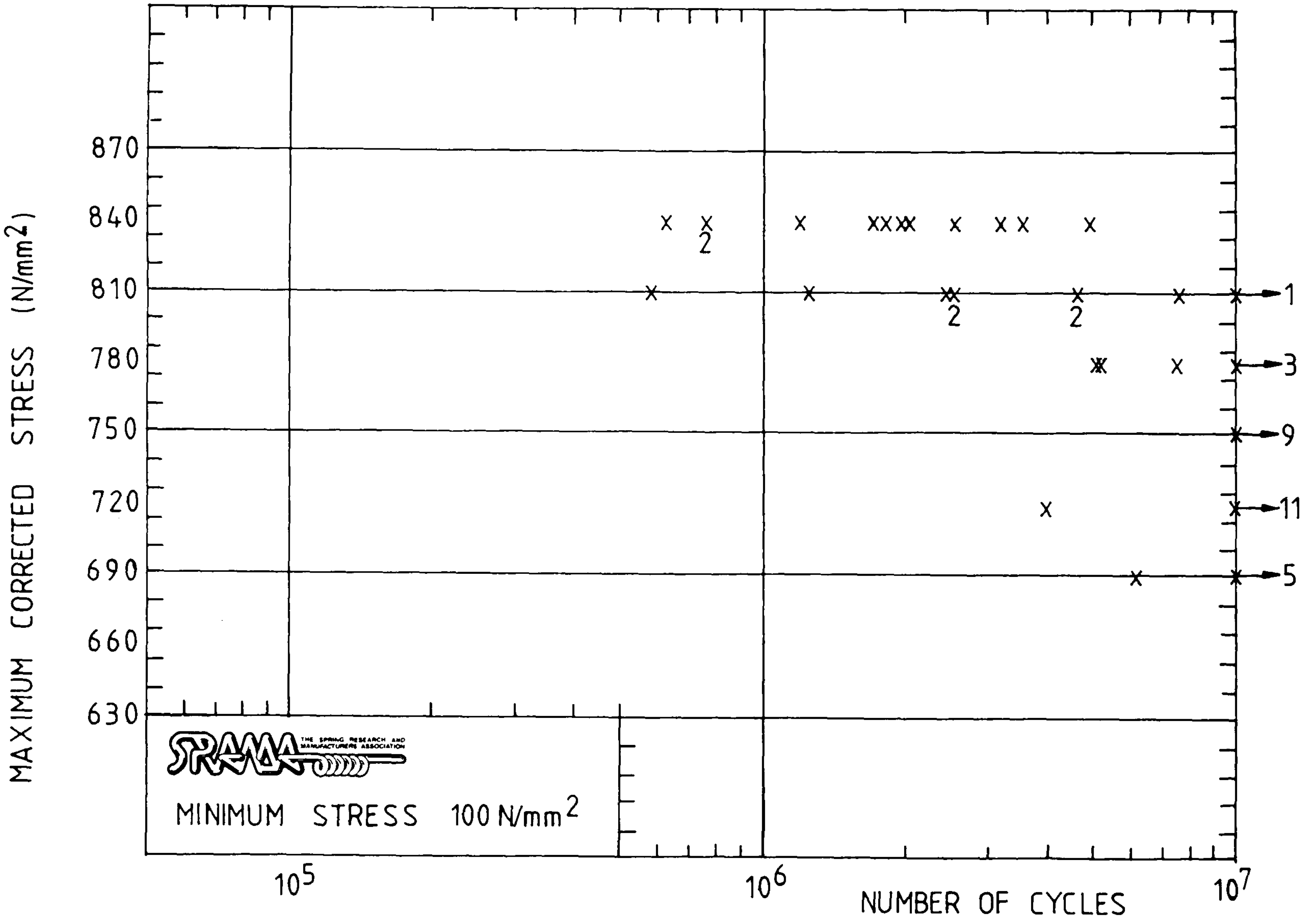

FIG 17. FATIGUE TEST RESULTS: BS 2803 C OK UNPEENED.

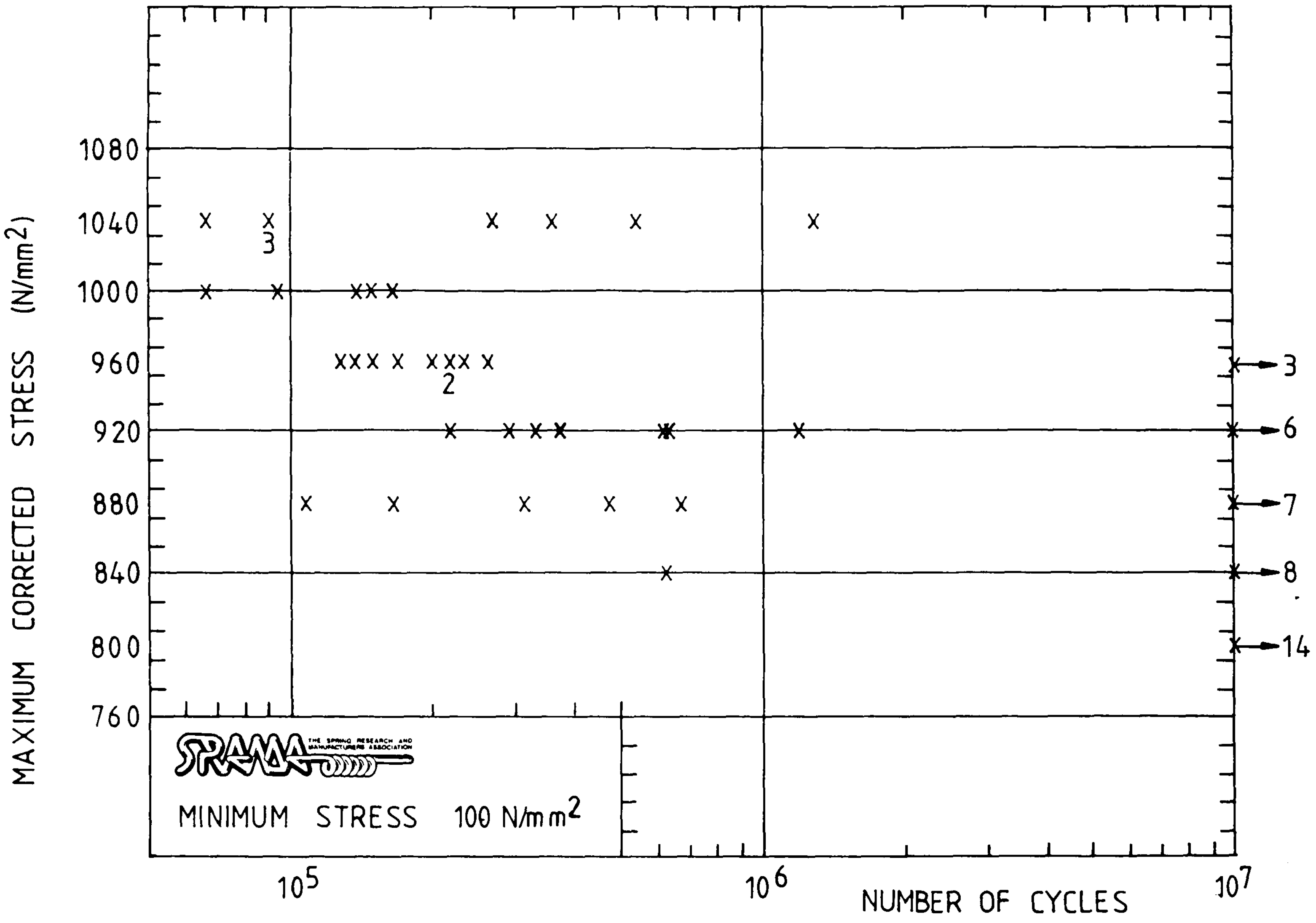

FIG 18. FATIGUE TEST RESULTS: BS 2803 C OK SHOTPEENED.

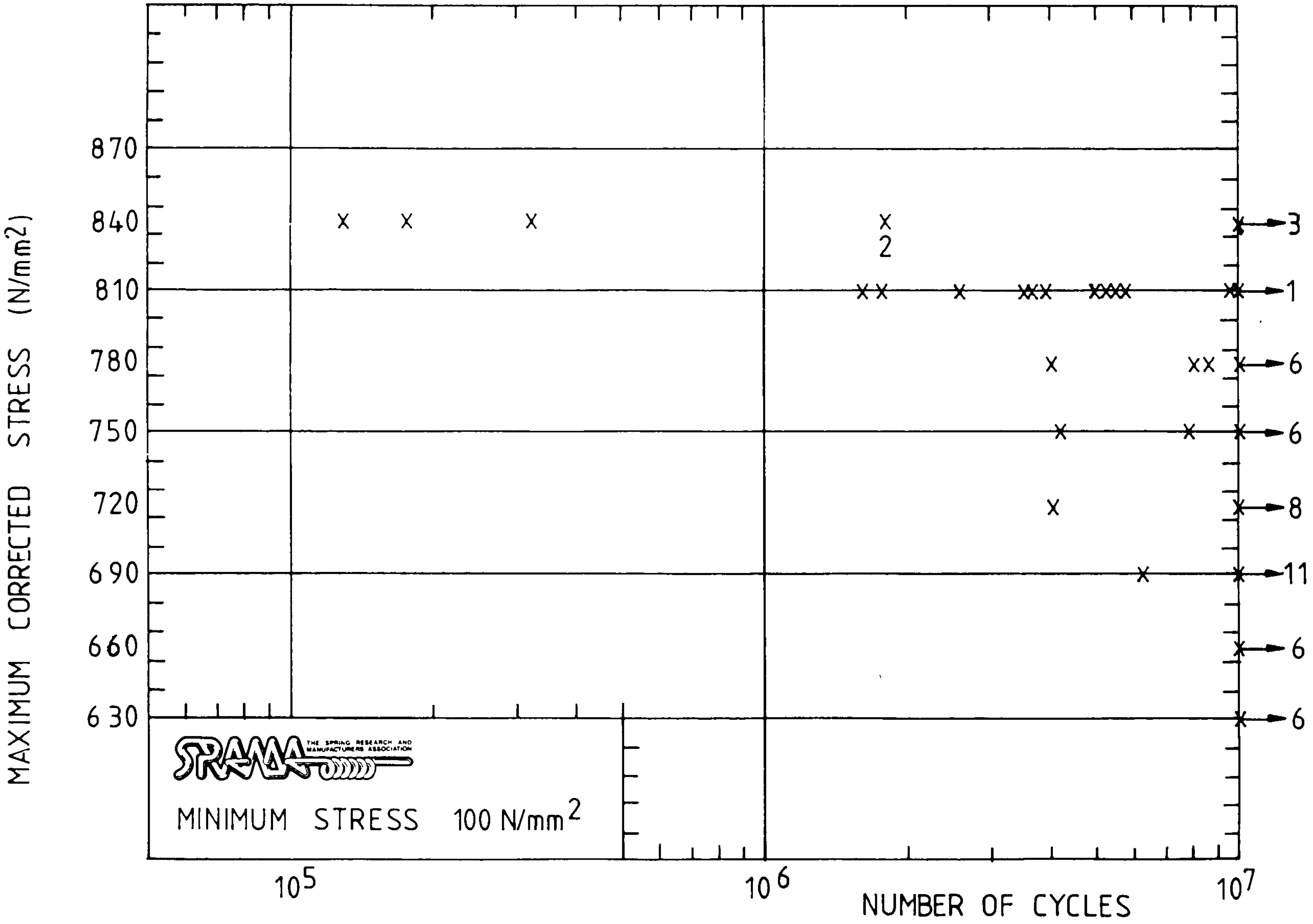

FIG 19. FATIGUE TEST RESULTS: BS 2803 C SDC UNPEENED.

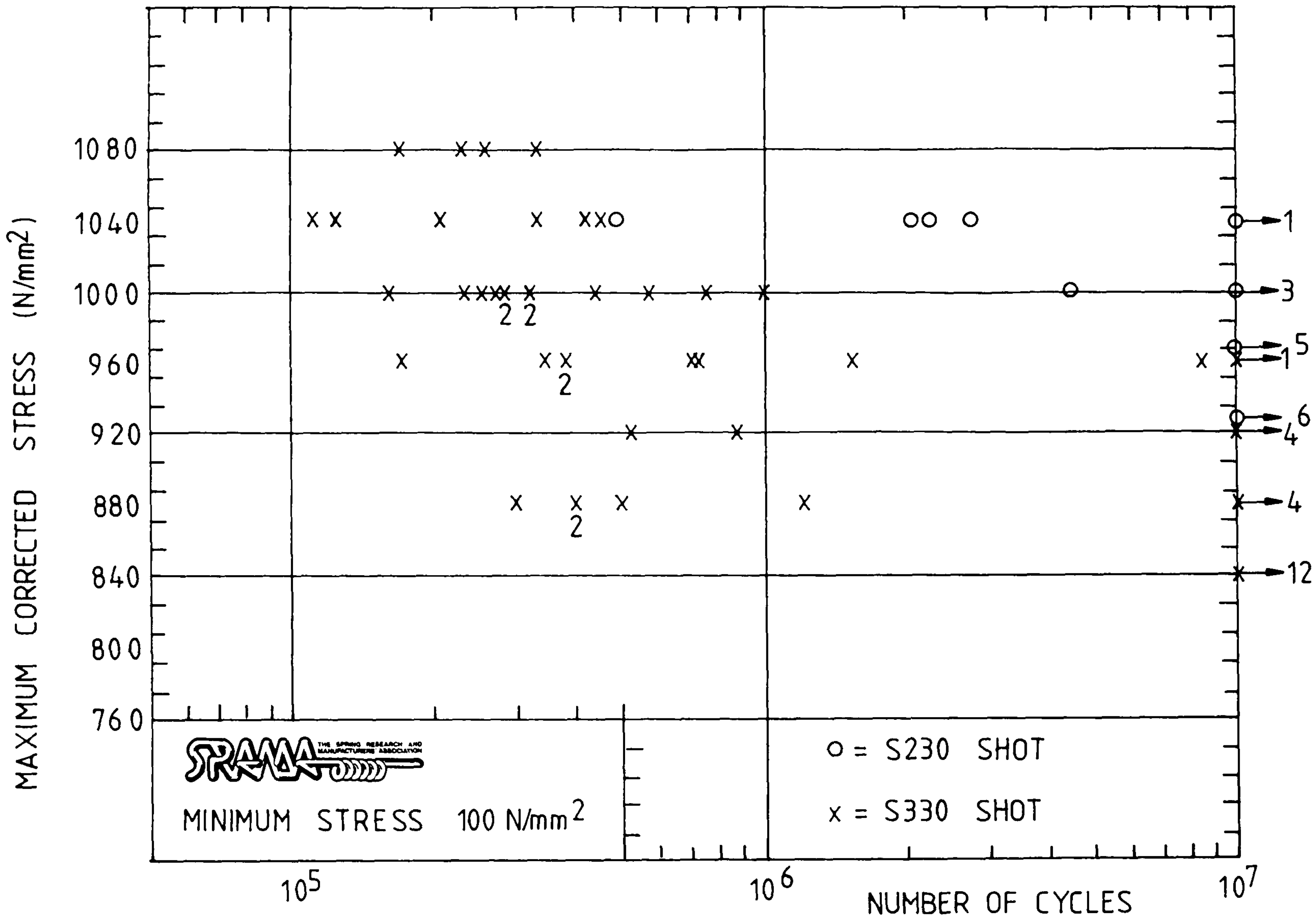

FIG 20. FATIGUE TEST RESULTS: BS 2803 C SDC SHOTPEENED.

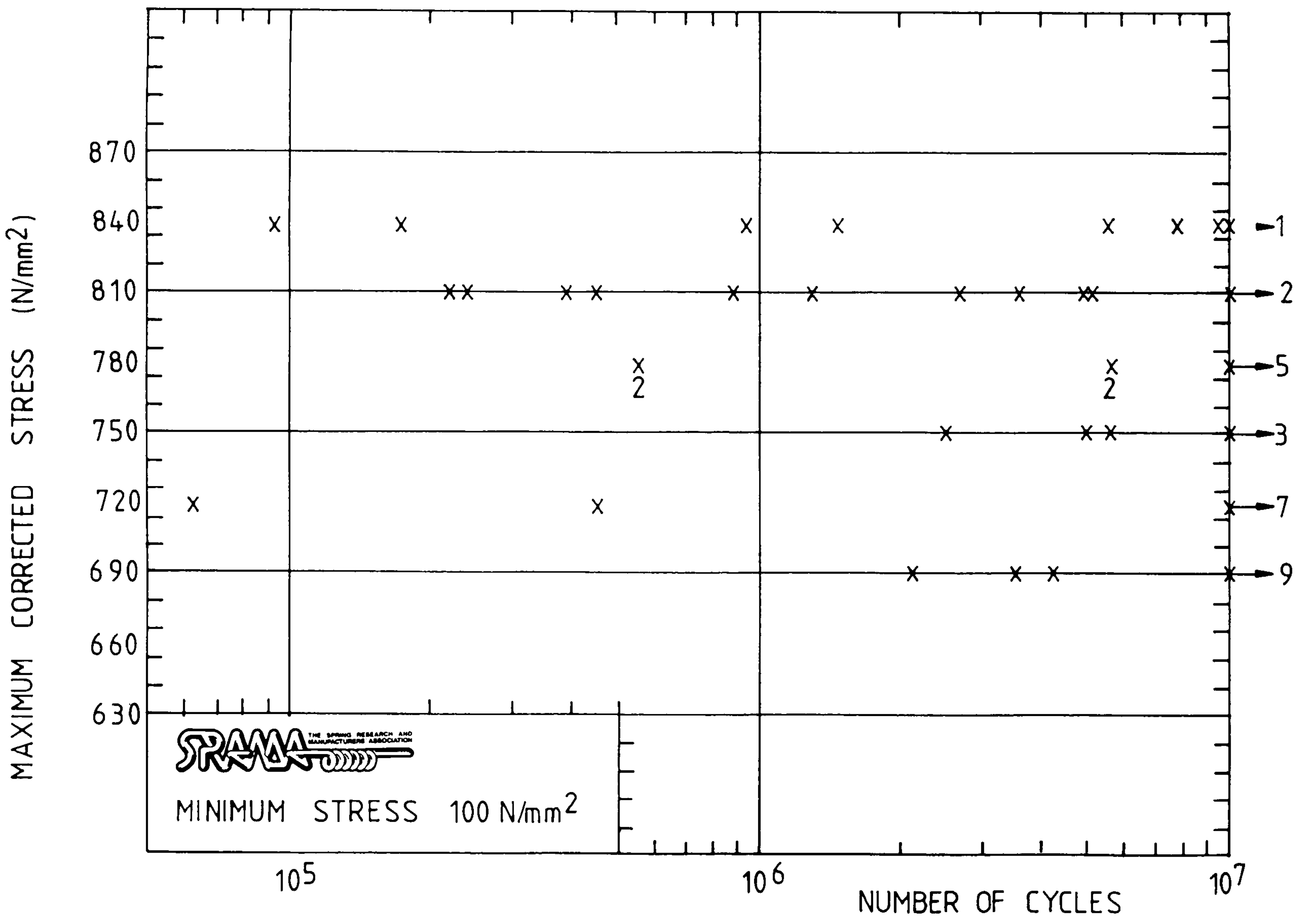

FIG 21. FATIGUE TEST RESULTS: BS 2803 C LDC UNPEENED.

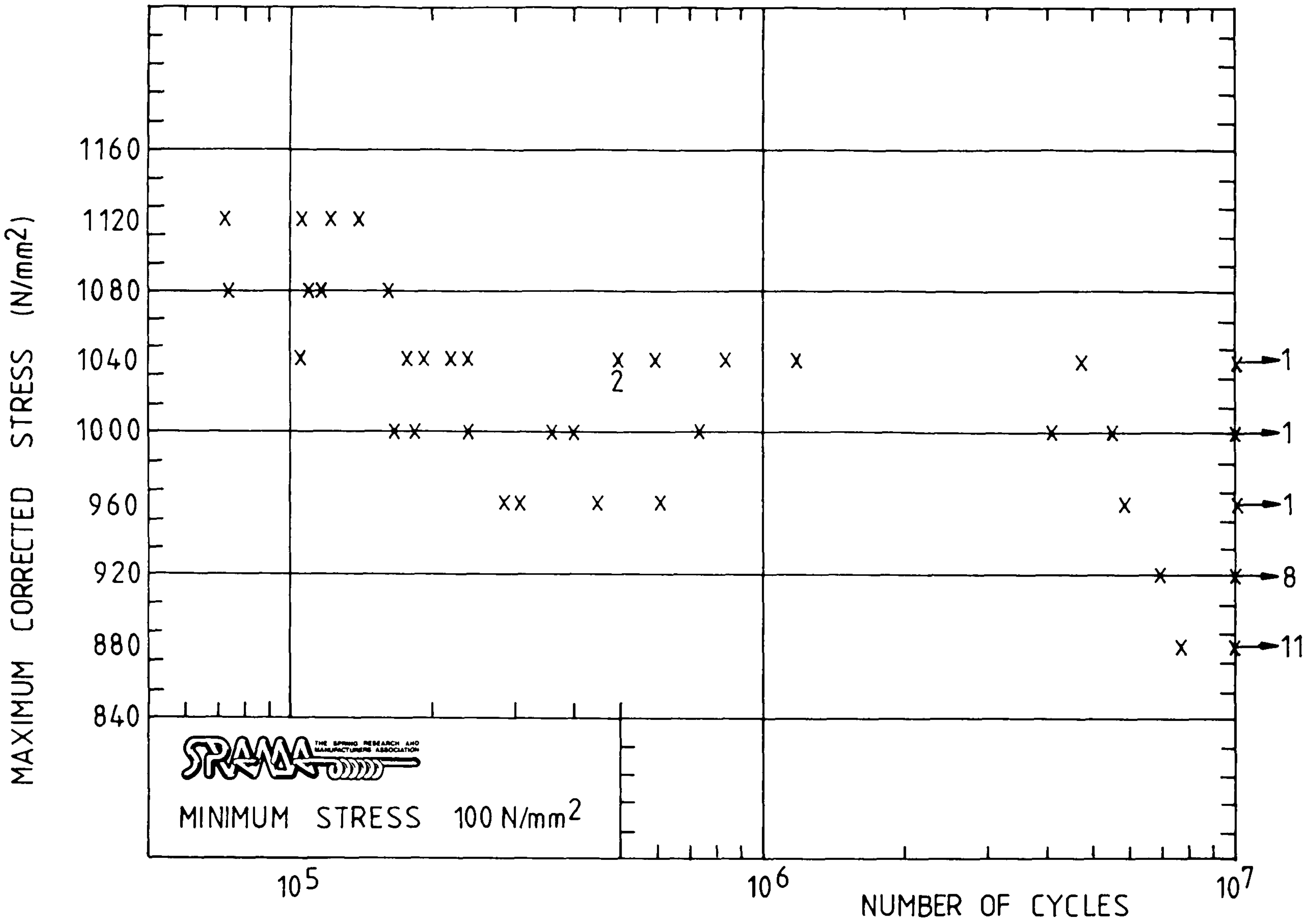

FIG 22. FATIGUE TEST RESULTS: BS 2803 C LDC SHOTPEENED.

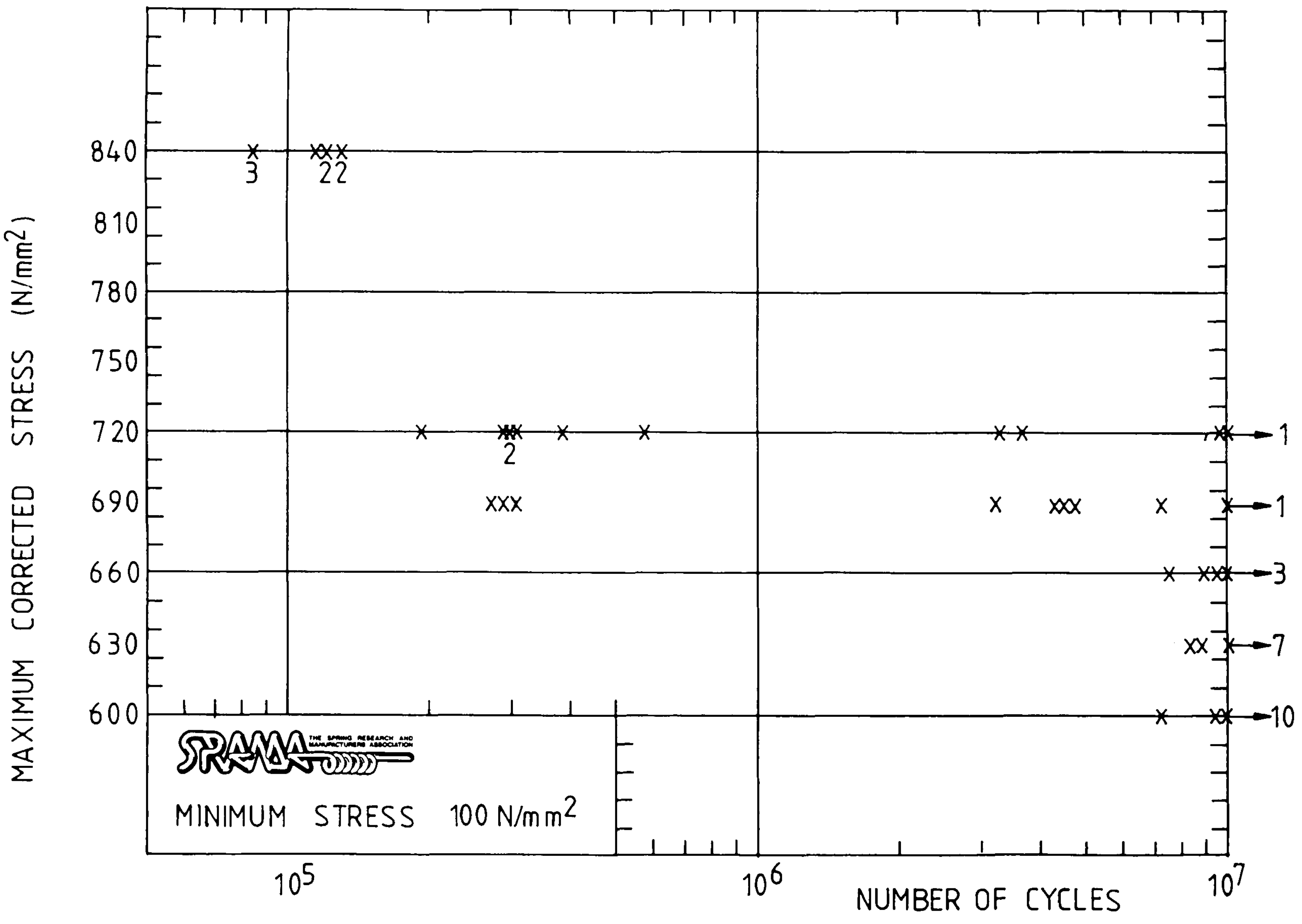

FIG 23. FATIGUE TEST RESULTS: BS 2803 C SDF UNPEENED.

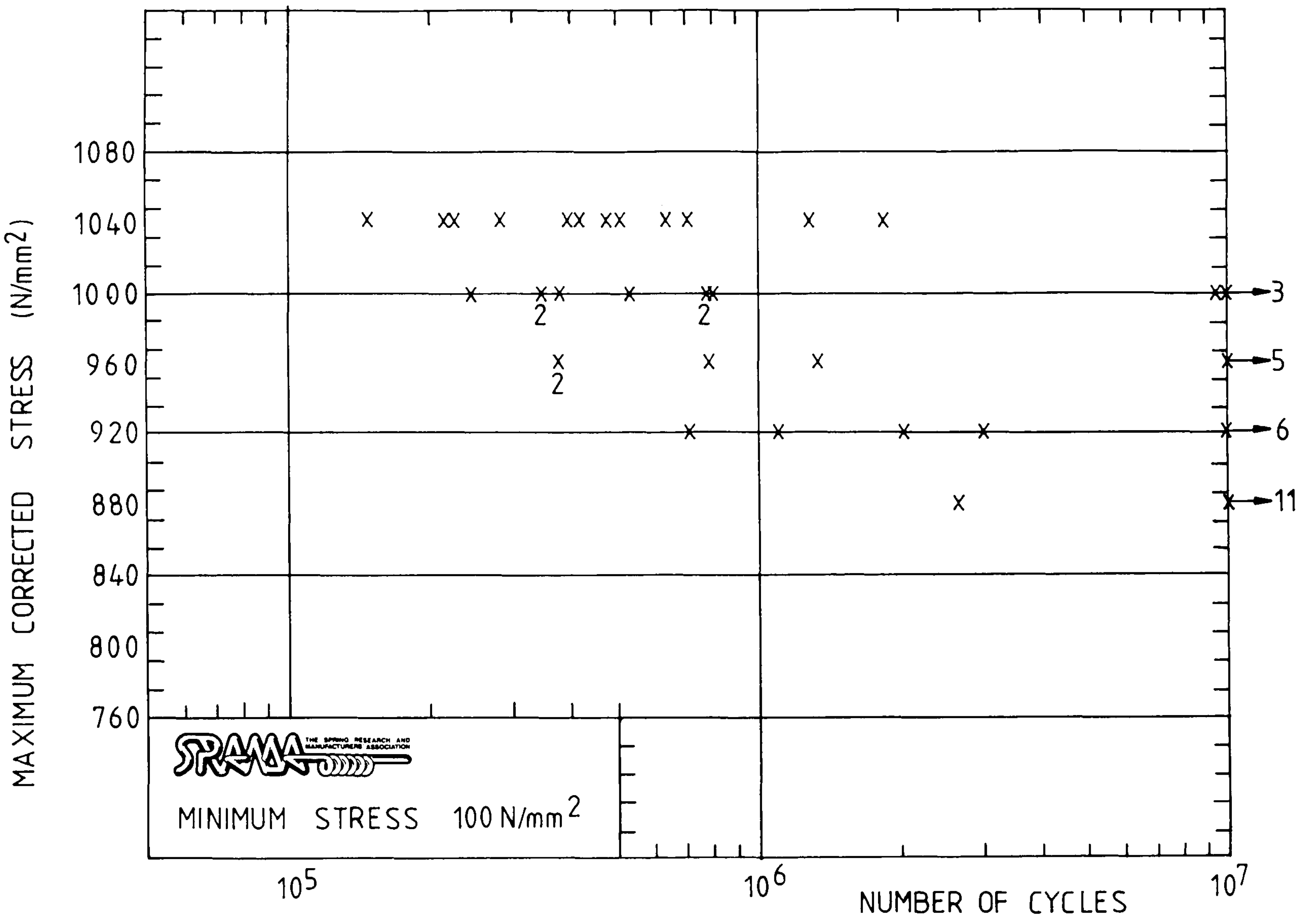

FIG 24. FATIGUE TEST RESULTS: BS 2803 C SDF SHOTPEENED.

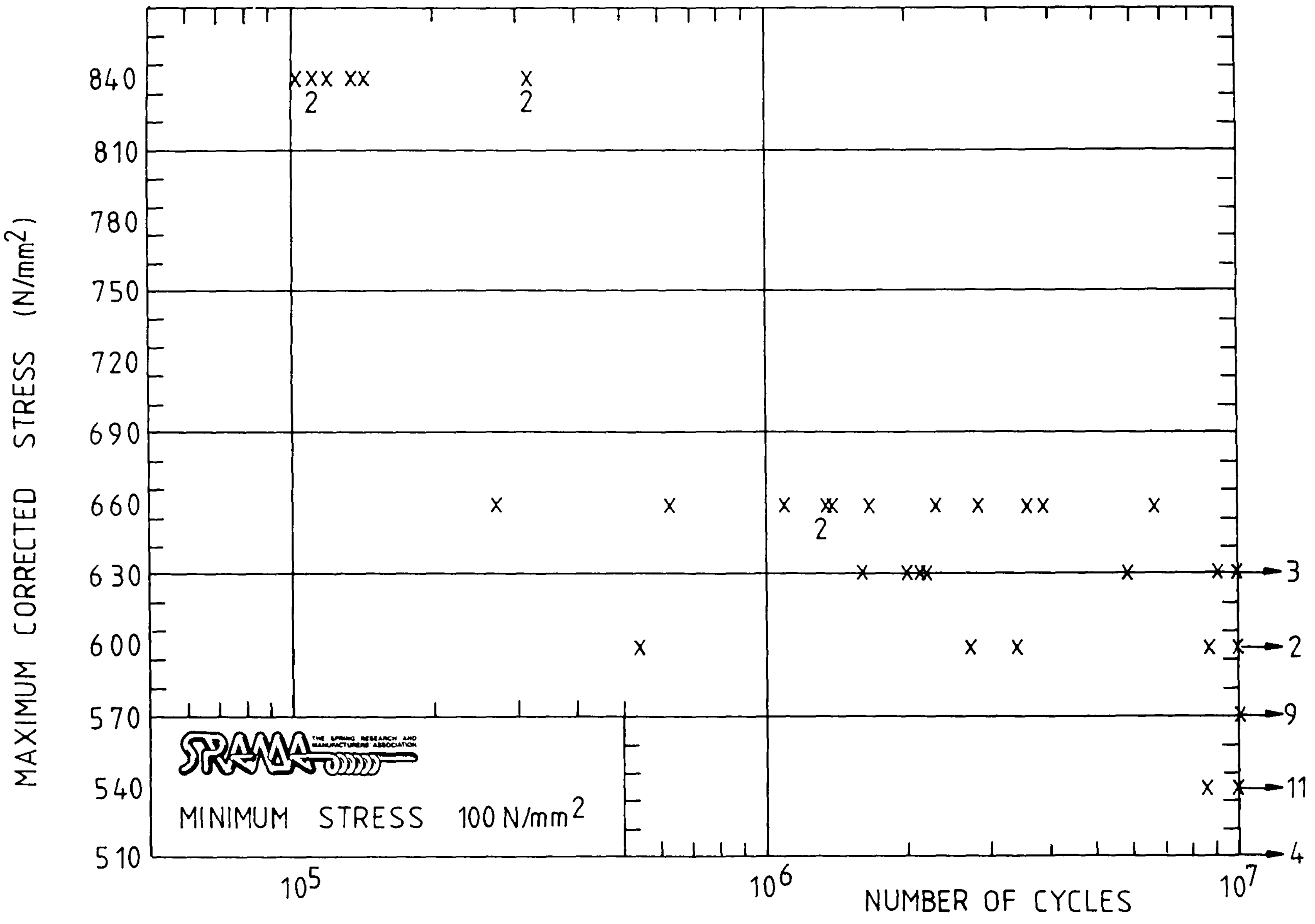

FIG 25. FATIGUE TEST RESULTS: BS 2803 C LDF UNPEENED.

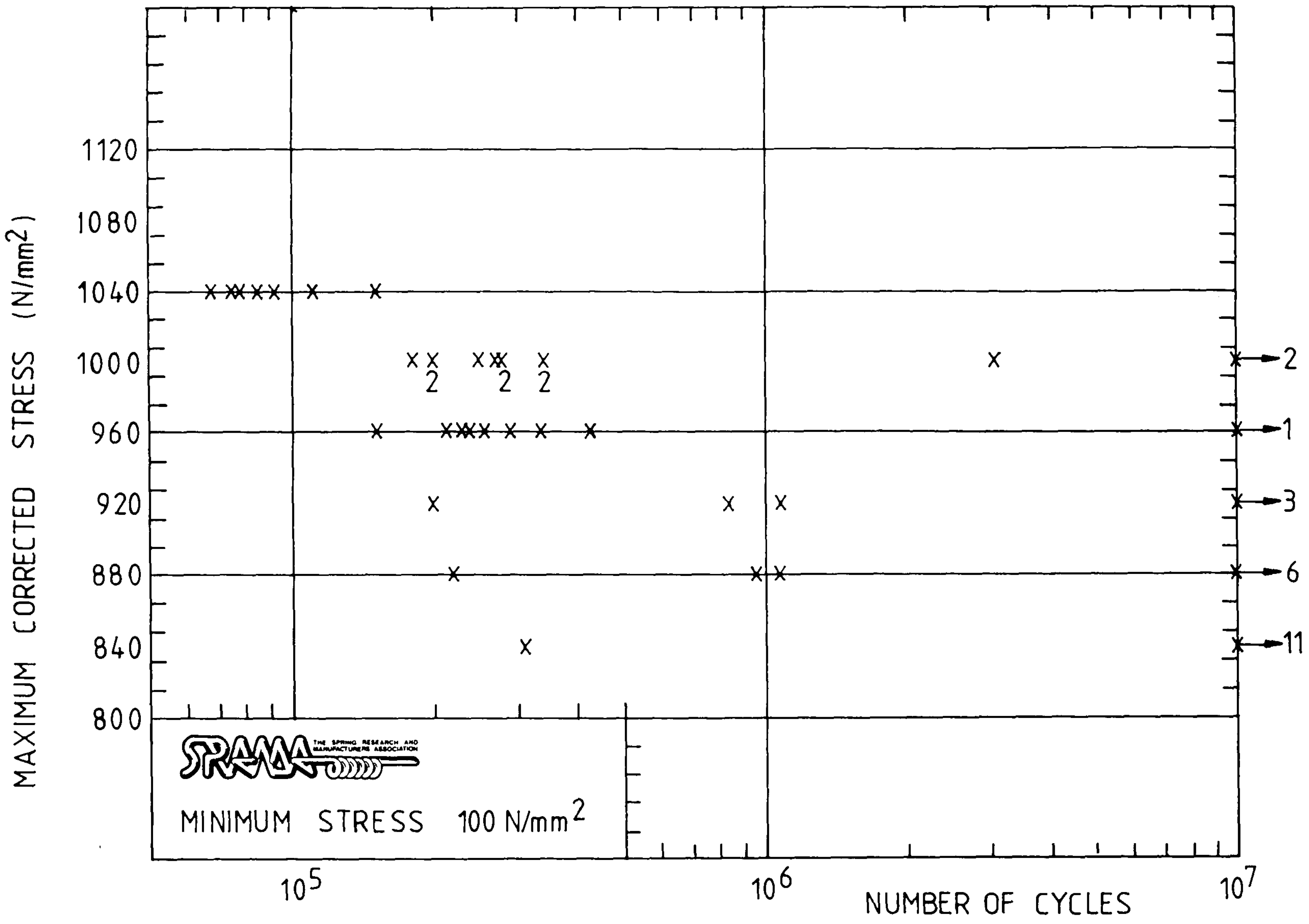

FIG 26. FATIGUE TEST RESULTS: BS 2803 C LDF SHOTPEENED.

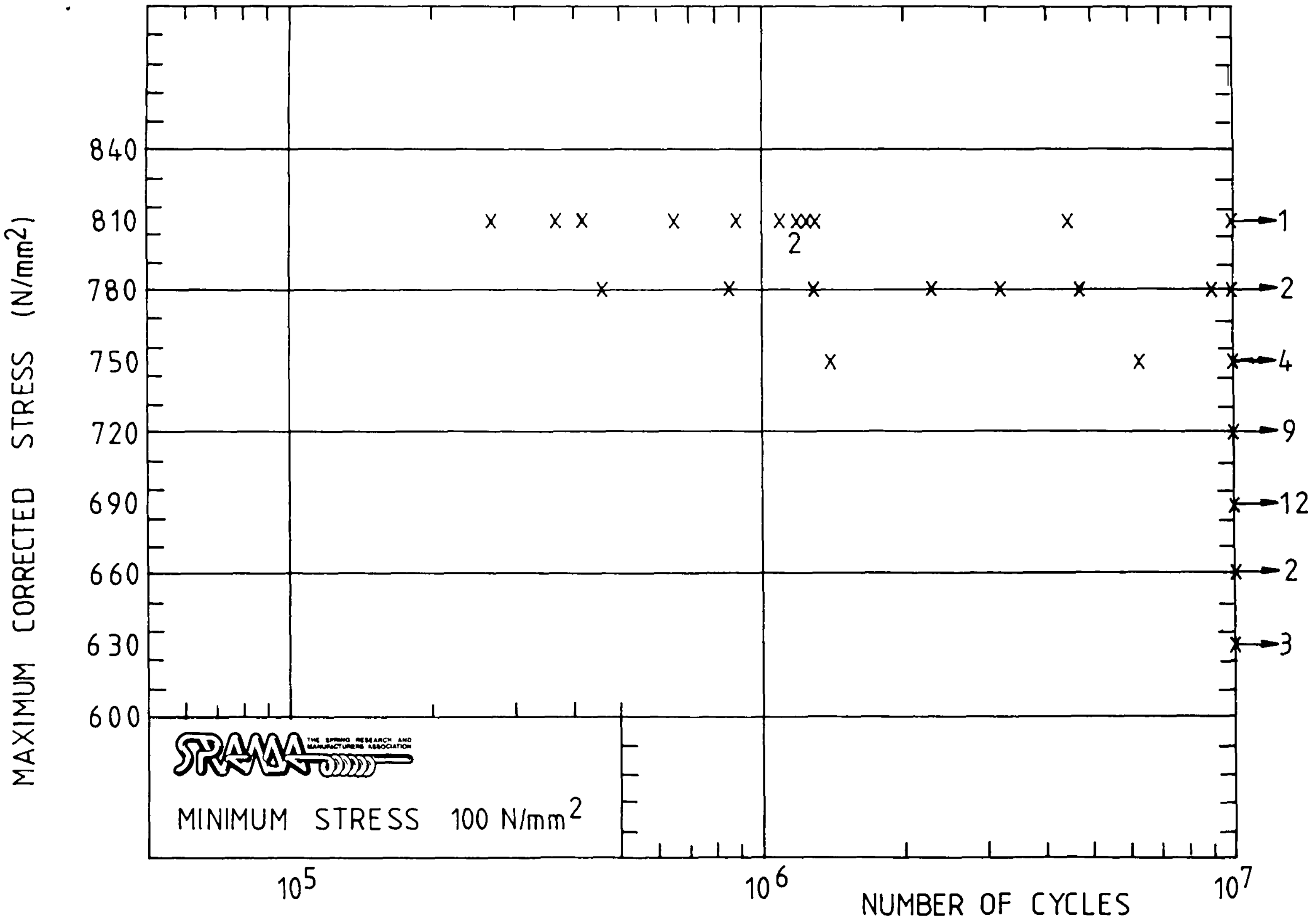

FIG 27 FATIGUE TEST RESULTS: BS 2803 CrV OK UNPEENED.

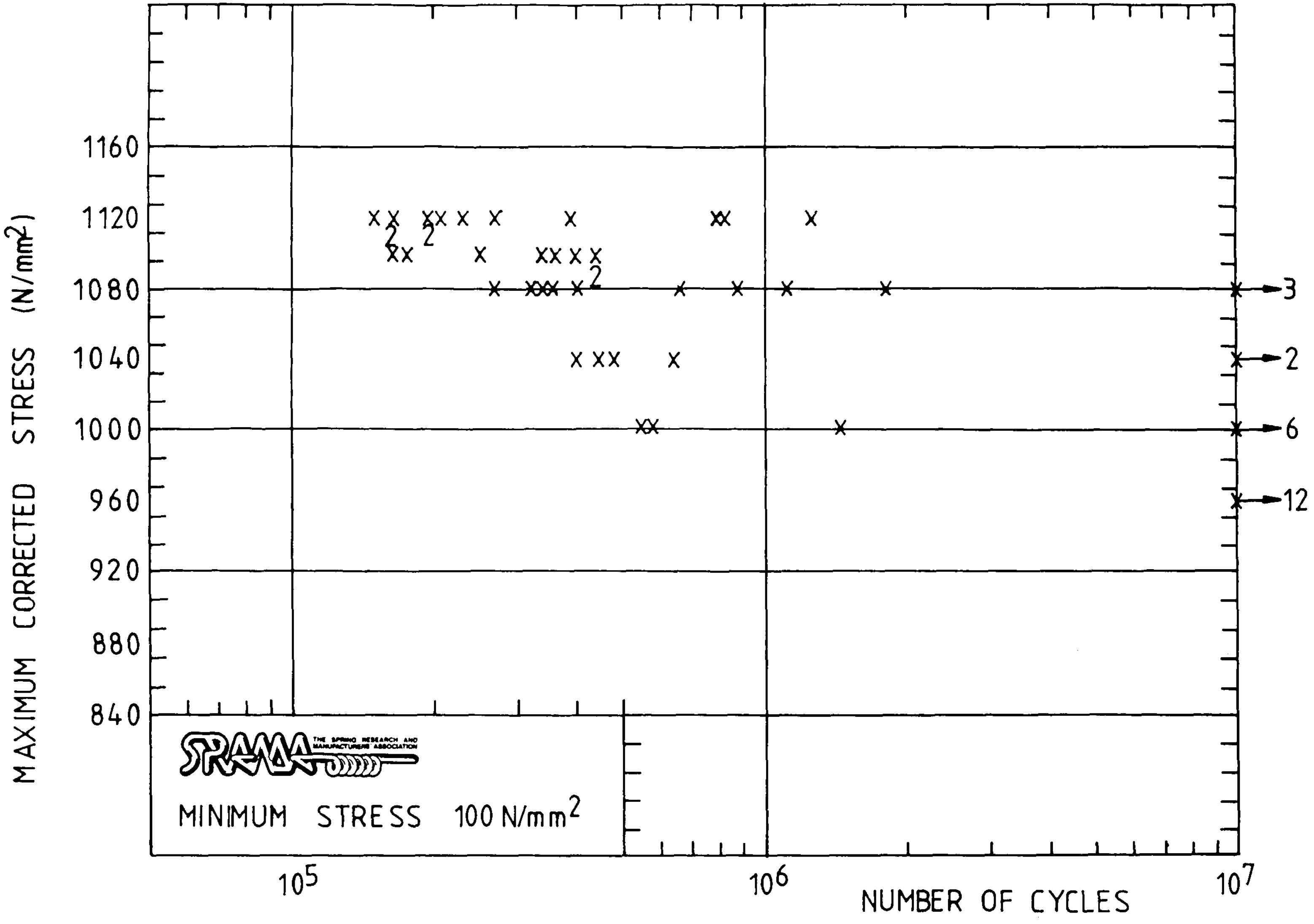

FIG 28. FATIGUE TEST RESULTS: BS 2803 CrV OK SHOTPEENED.

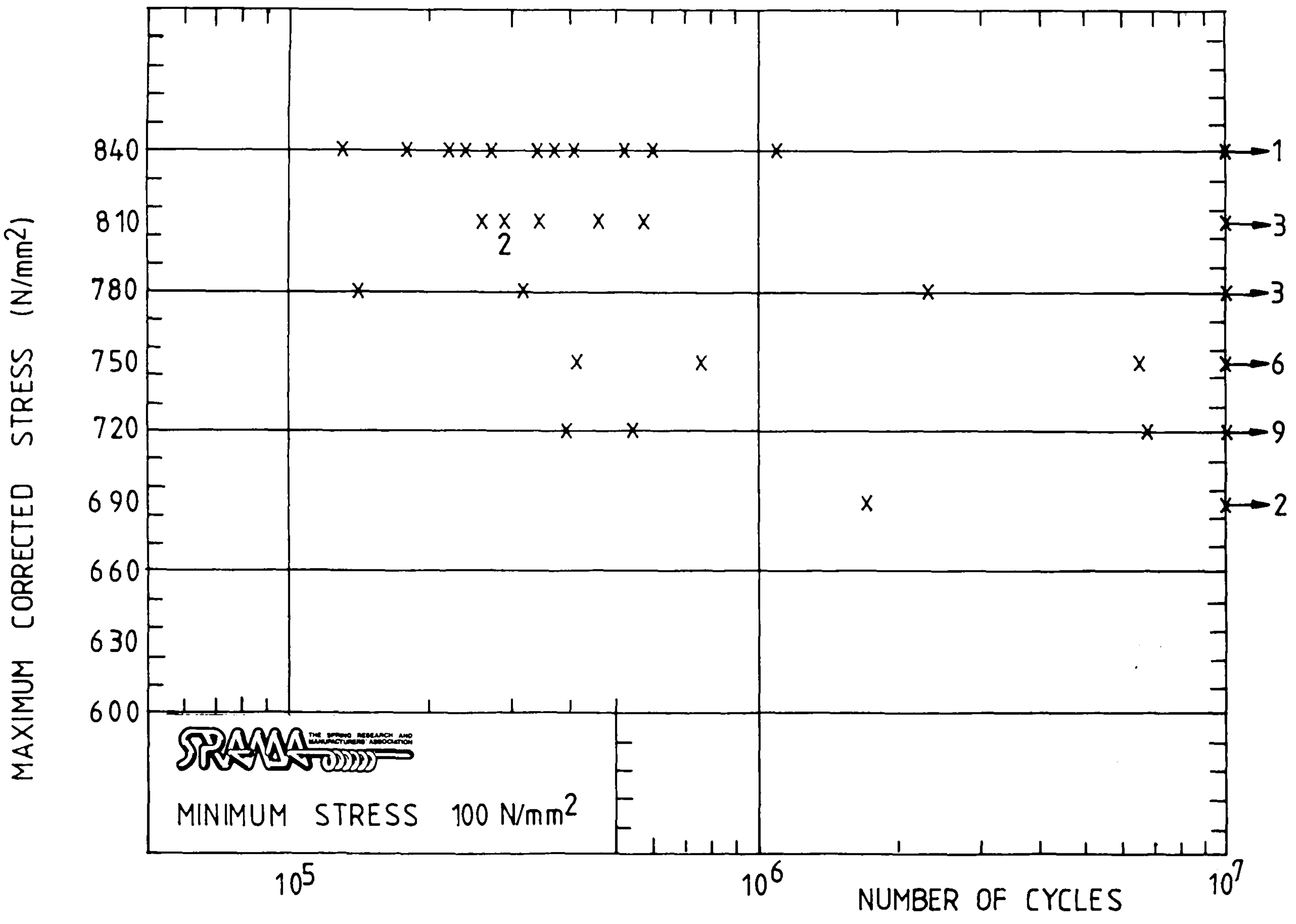

FIG 29. FATIGUE TEST RESULTS: BS 2803 CrV SDC UNPEENED.

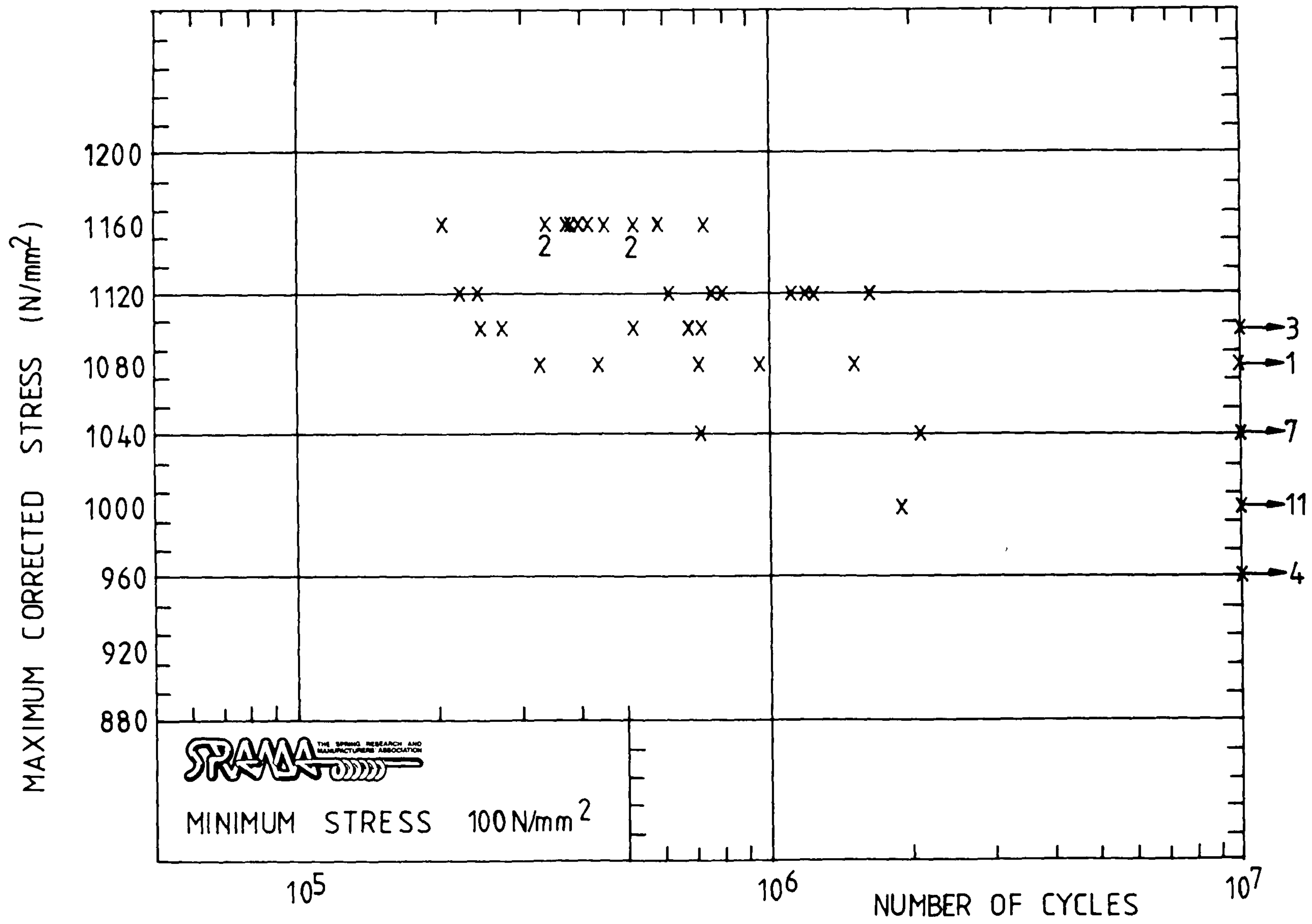

FIG 30. FATIGUE TEST RESULTS: BS 2803 CrV SDC SHOTPEENED.

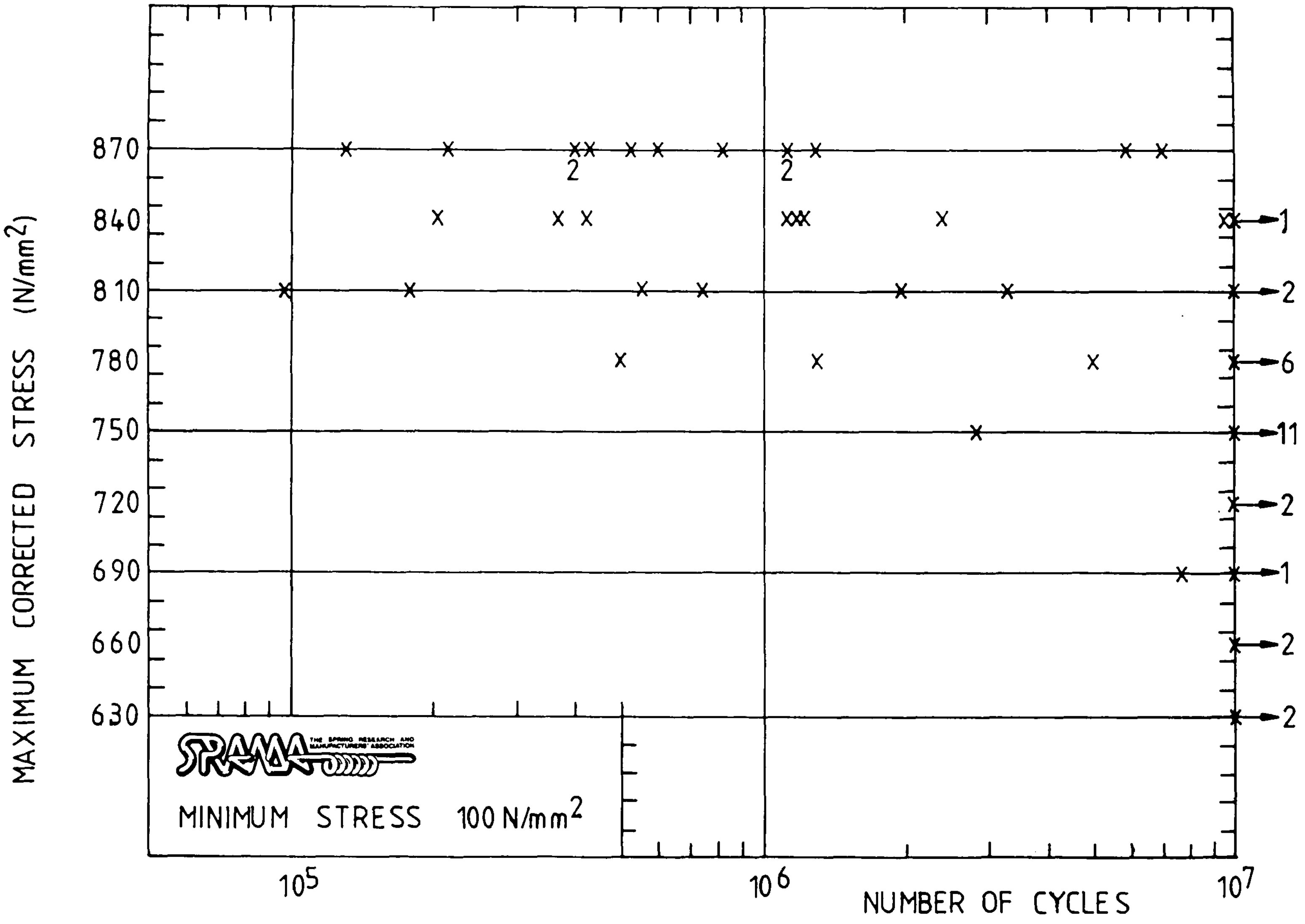

FIG 31. FATIGUE TEST RESULTS: BS 2803 CrV LDC UNPEENED.

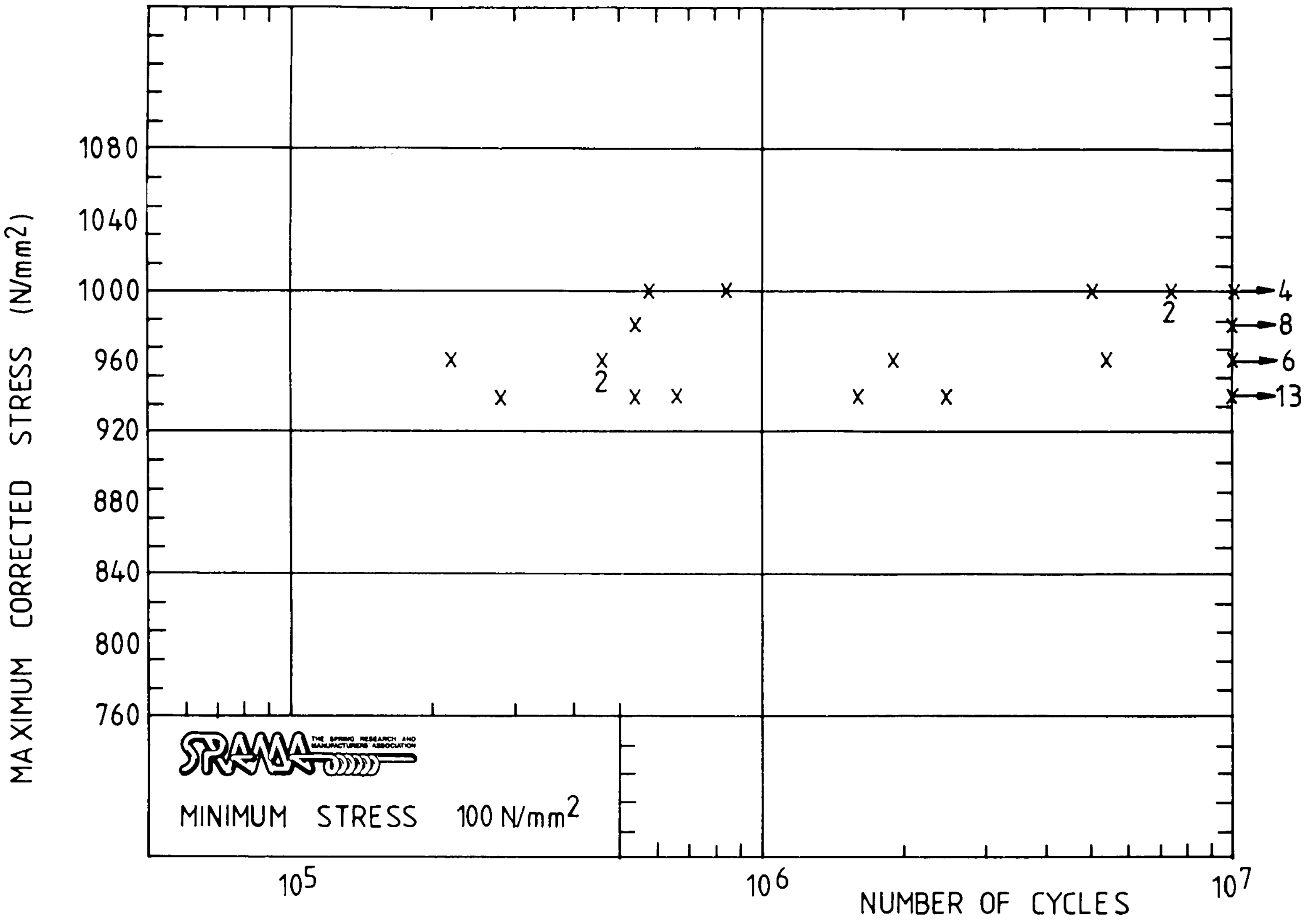

FIG 32. FATIGUE TEST RESULTS: BS 2803 CrV LDC SHOTPEENED.

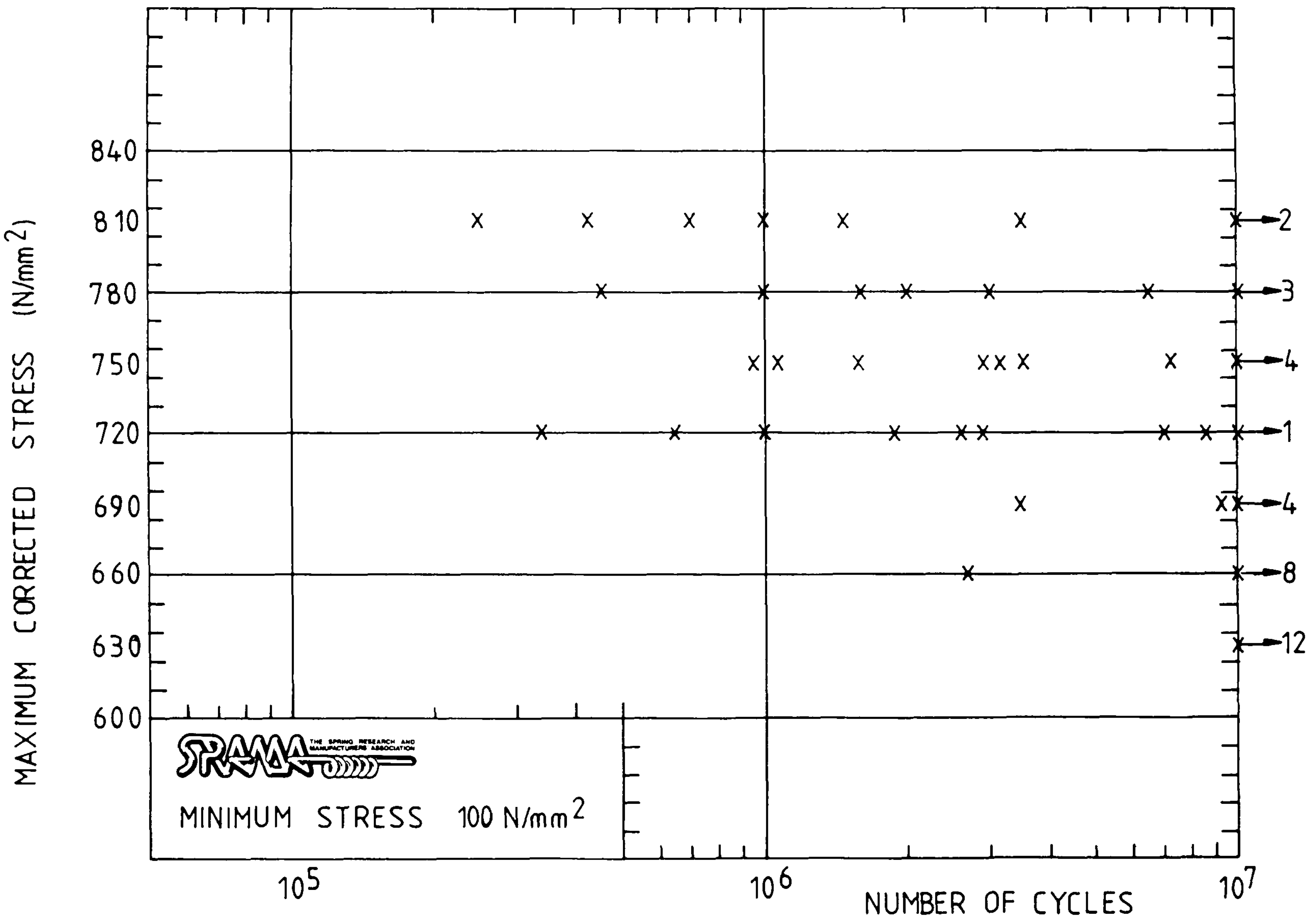

FIG 33. FATIGUE TEST RESULTS: BS 2803 CrV SDF UNPEENED.

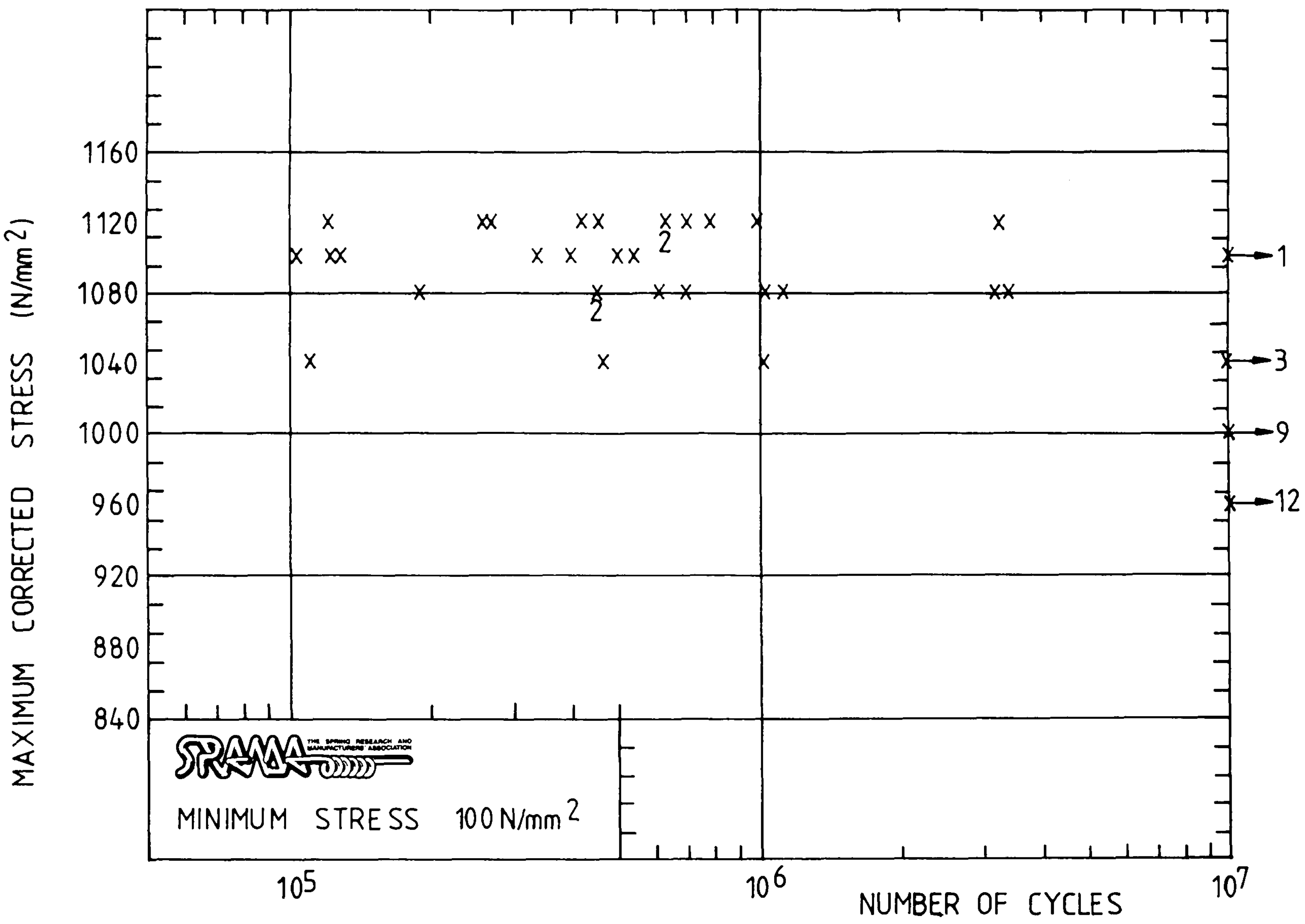

FIG 34. FATIGUE TEST RESULTS: BS 2803 CrV SDF SHOTPEENED.

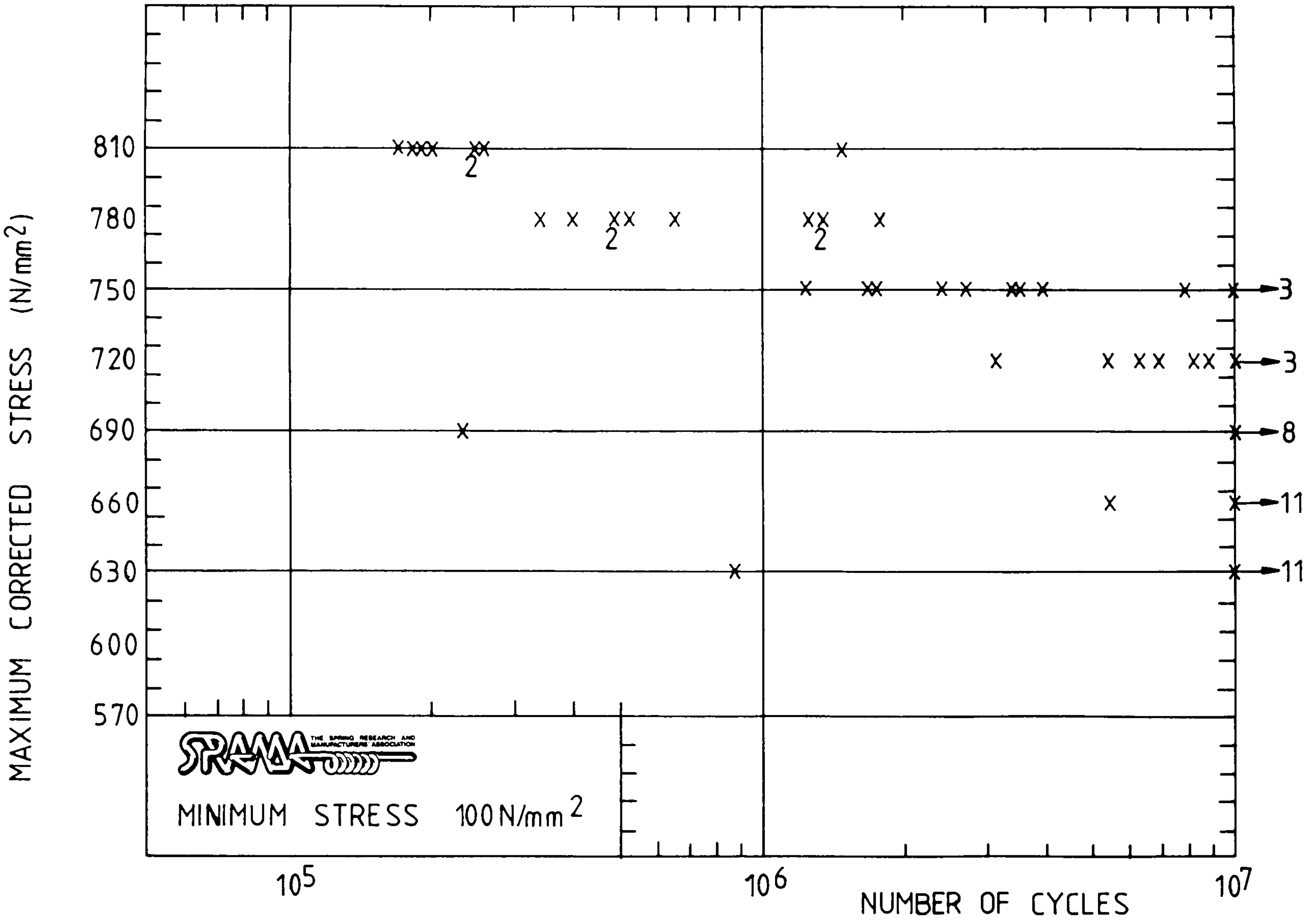

FIG 35. FATIGUE TEST RESULTS: BS 2803 CrV LDF UNPEENED.

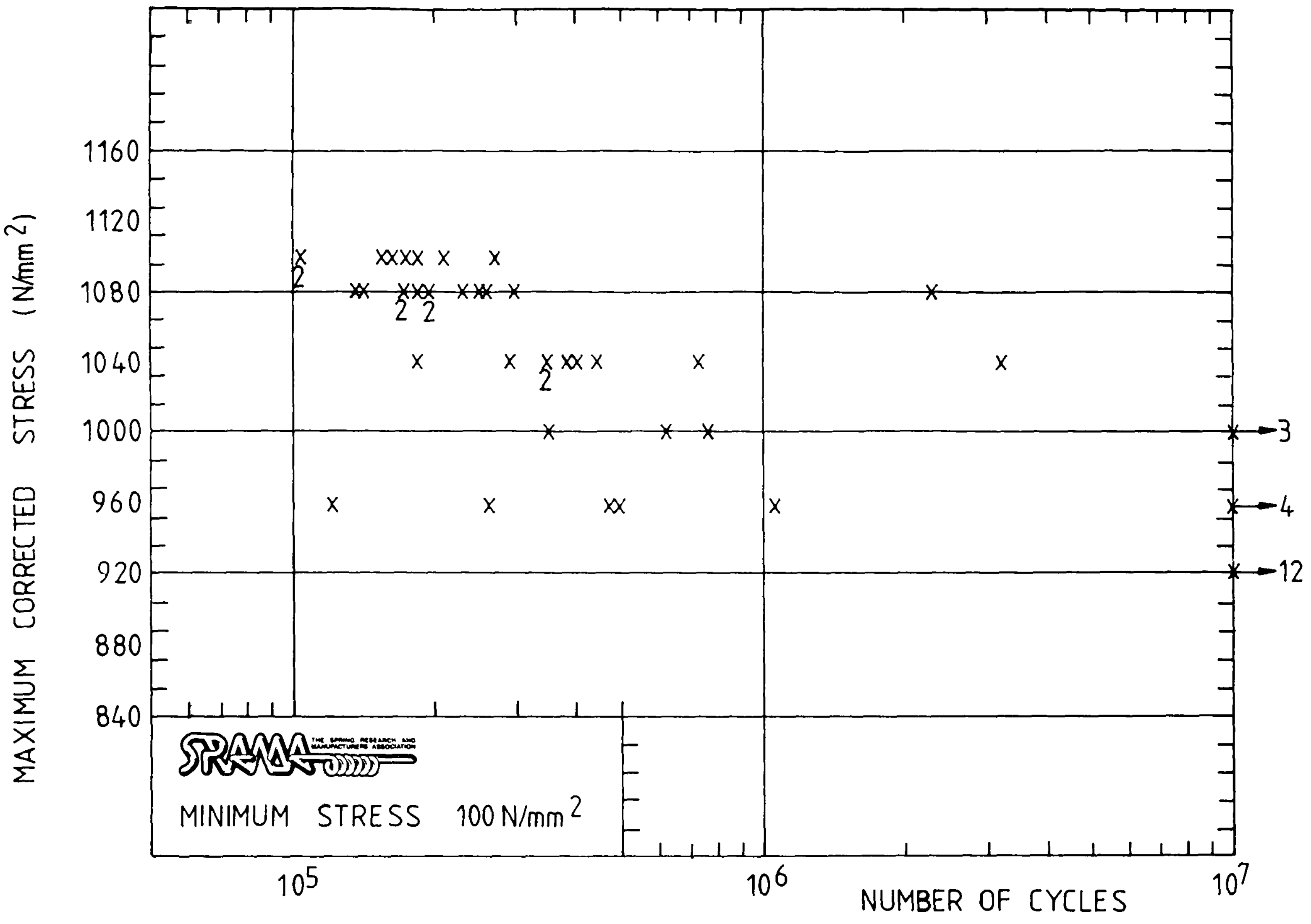

FIG 36. FATIGUE TEST RESULTS: BS 2803 CrV LDF SHOTPEENED.

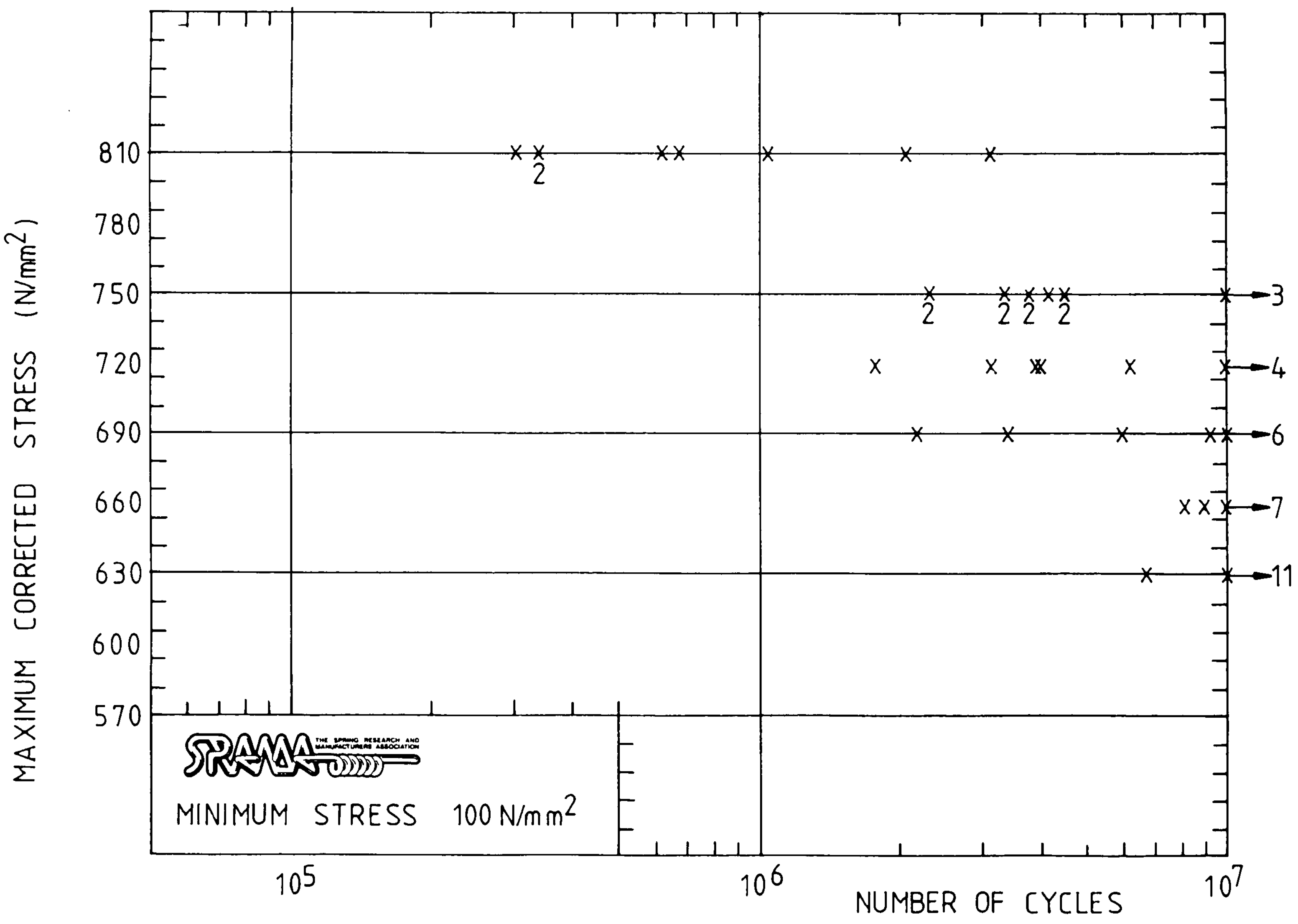

FIG 37. FATIGUE TEST RESULTS: BS 2803 SiC OK UNPEENED.

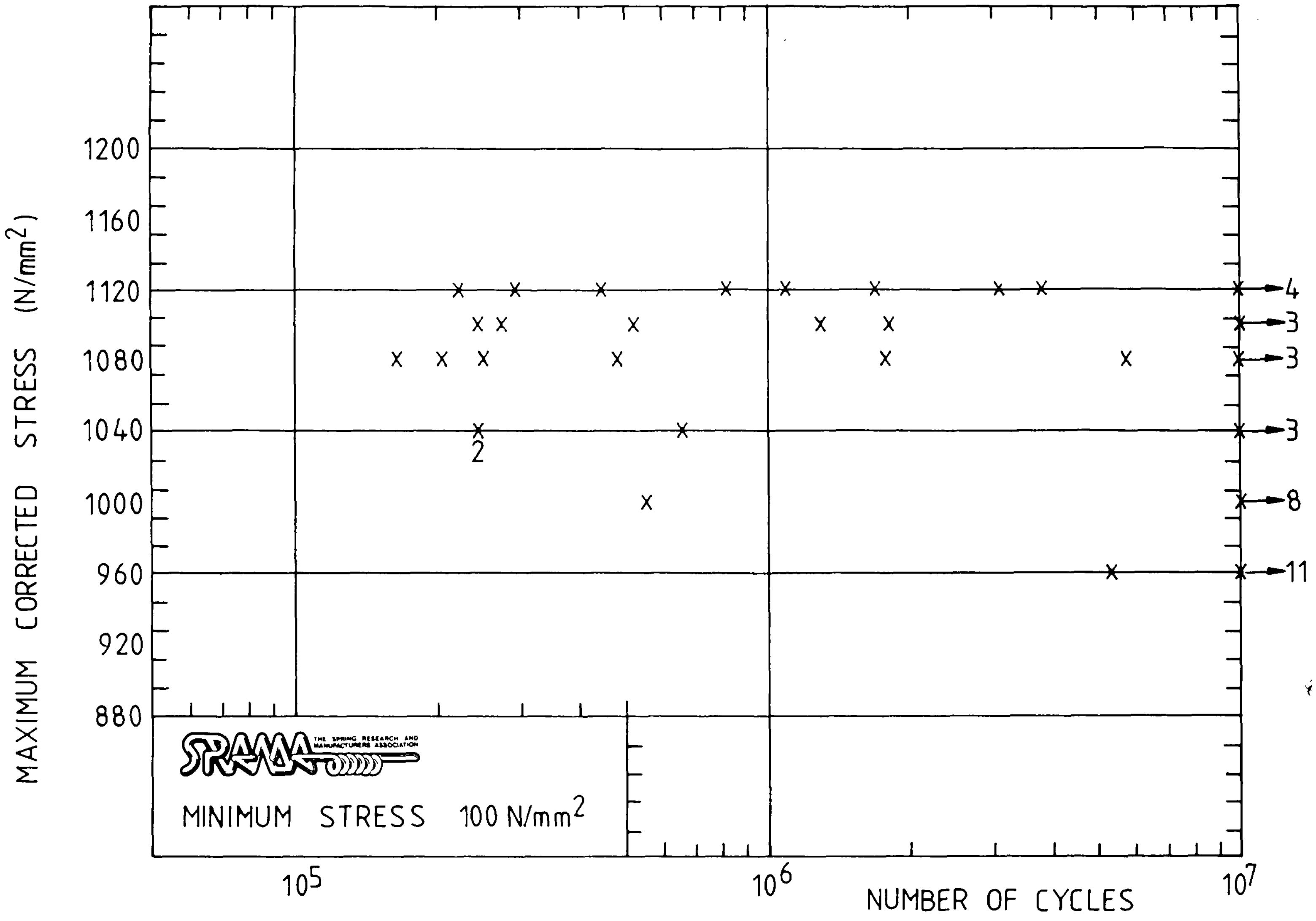

FIG 38. FATIGUE TEST RESULTS: BS 2803 SiC OK SHOTPEENED.

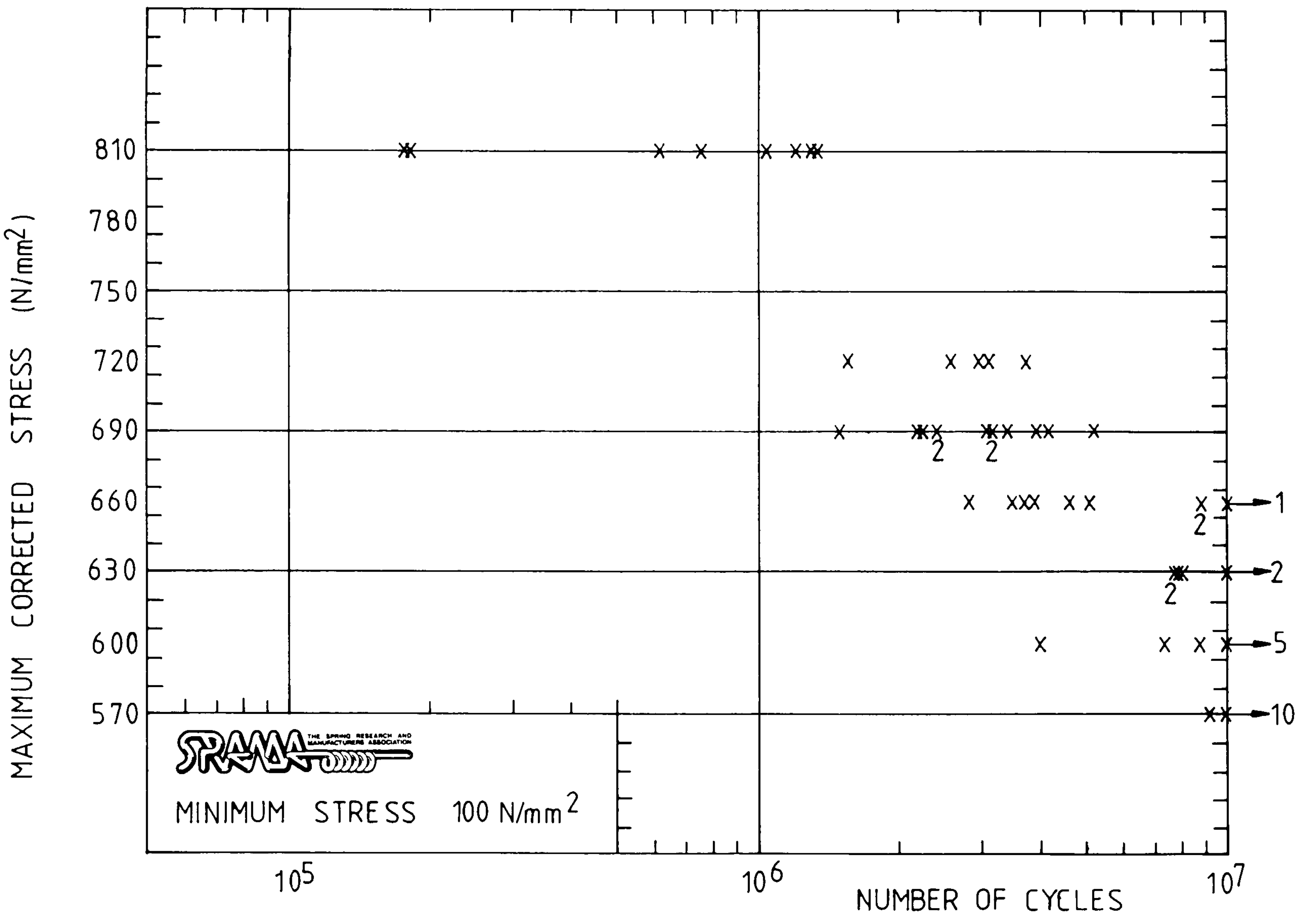

FIG 39. FATIGUE TEST RESULTS: BS 2803 SDC SiC UNPEENED.

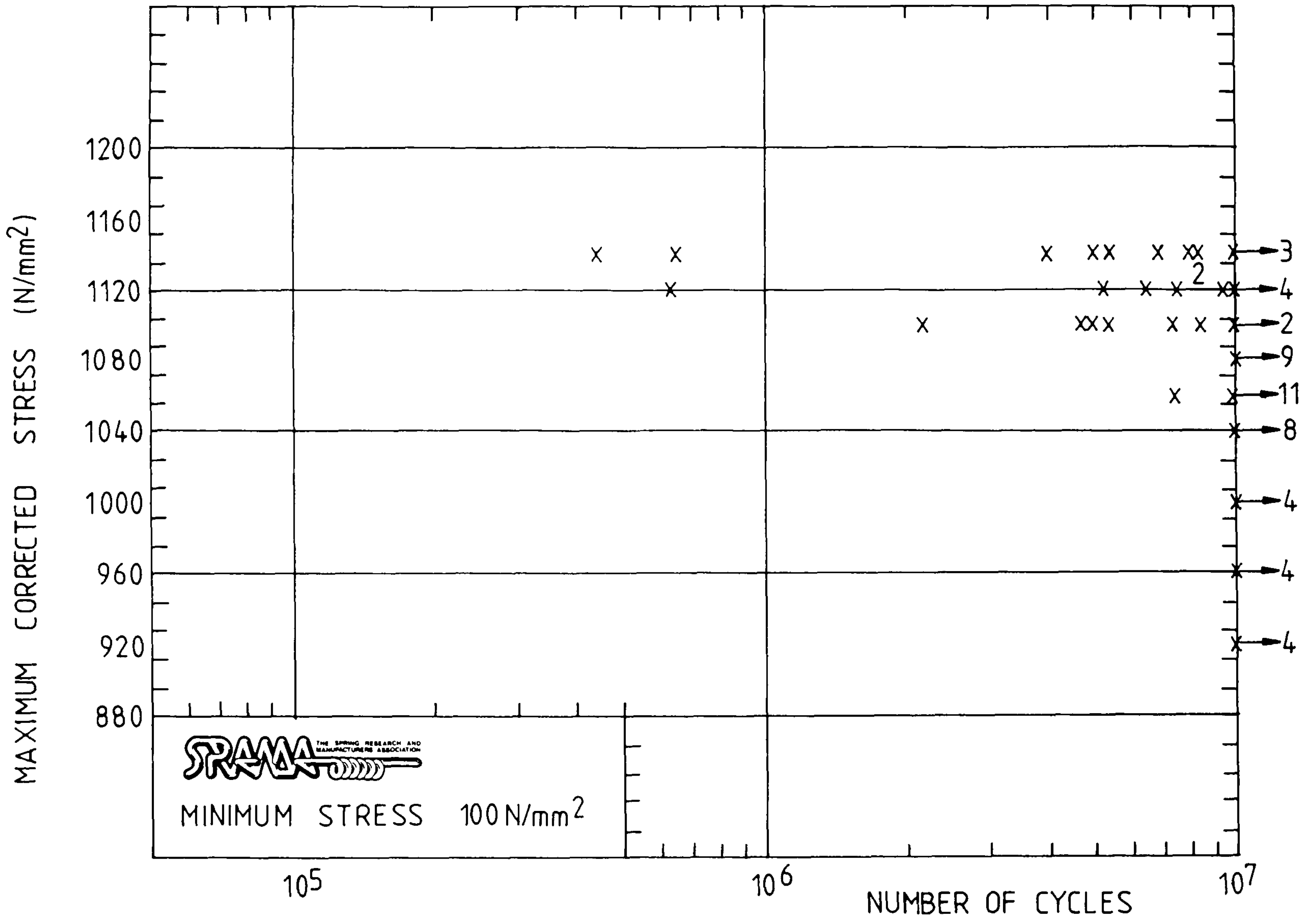

FIG 40. FATIGUE TEST RESULTS: BS 2803 SiC SDC SHOTPEENED.

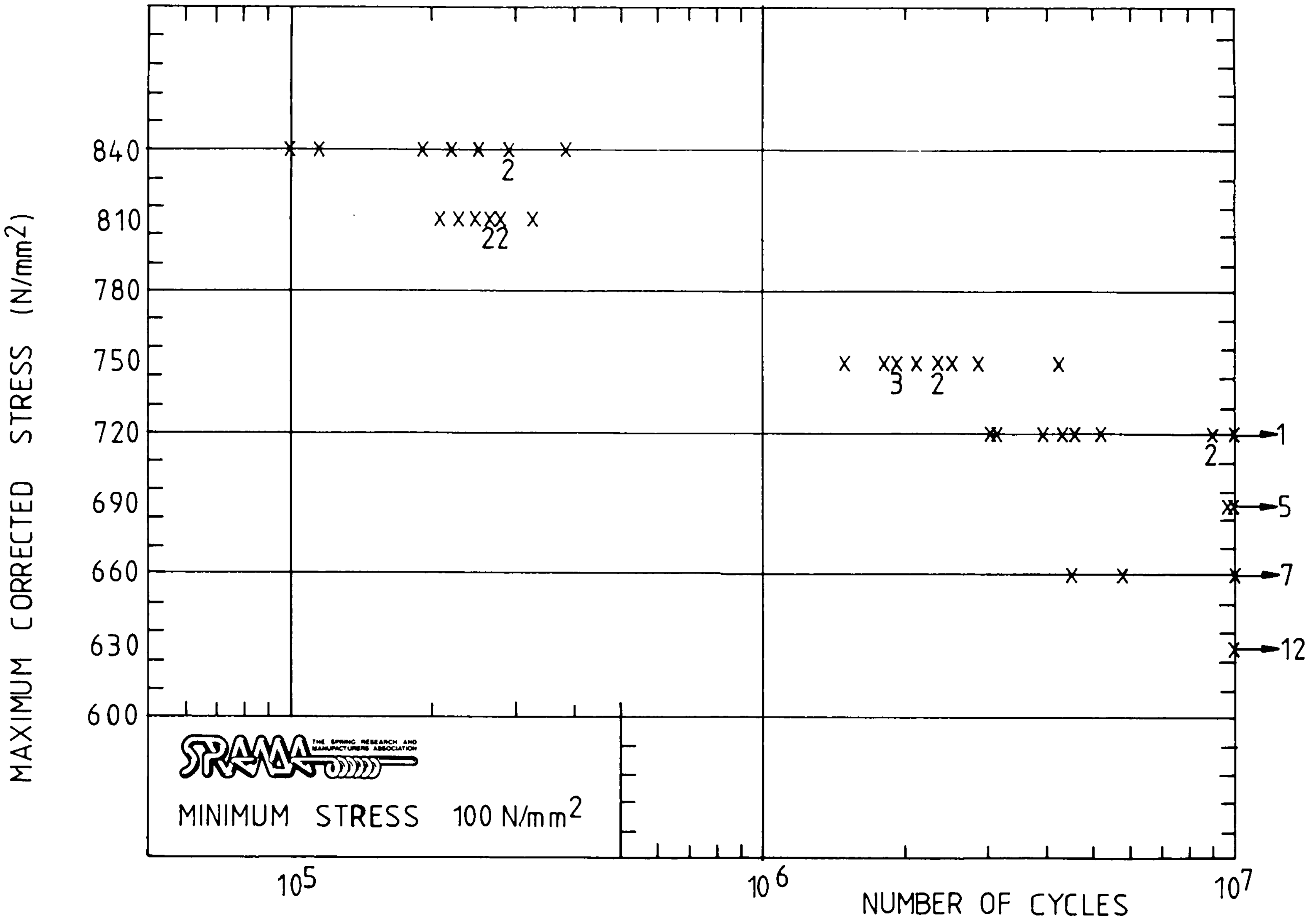

FIG 41. FATIGUE TEST RESULTS: BS 2803 SiC LDC UNPEENED.

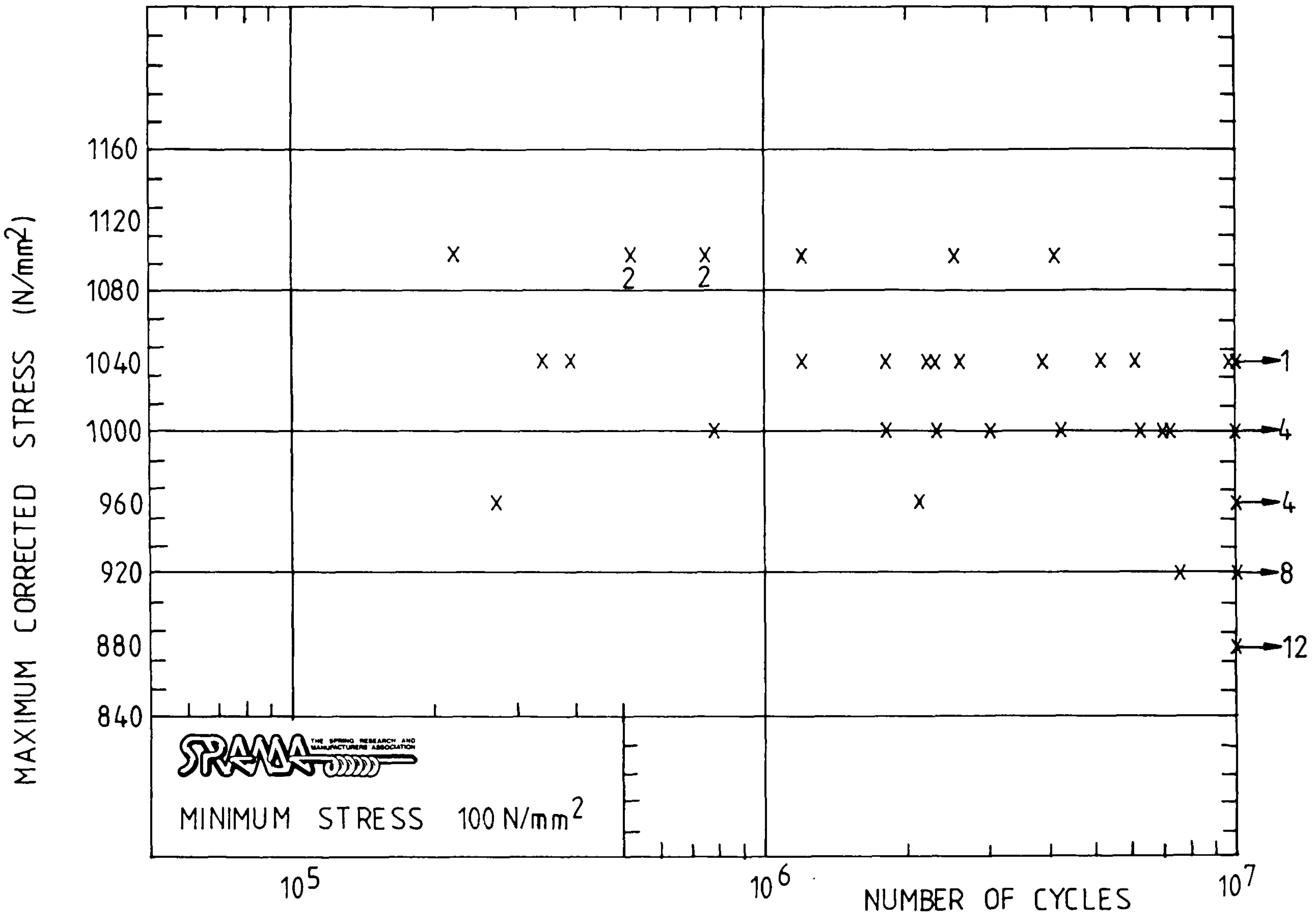

FIG 42. FATIGUE TEST RESULTS: BS 2803 SiC LDC SHOTPEENED.

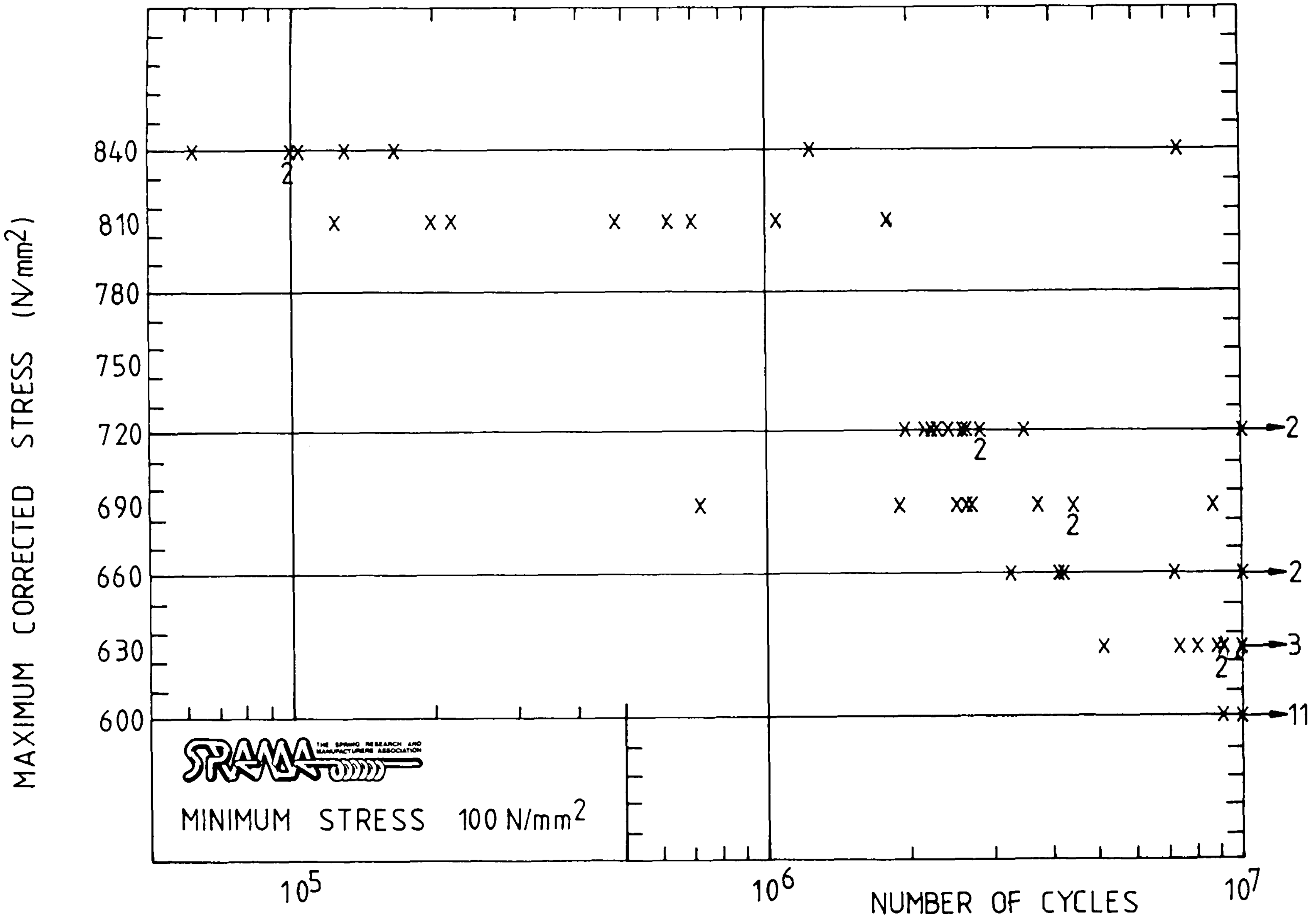

FIG 43. FATIGUE TEST RESULTS: BS 2803 SiC SDF UNPEENED.

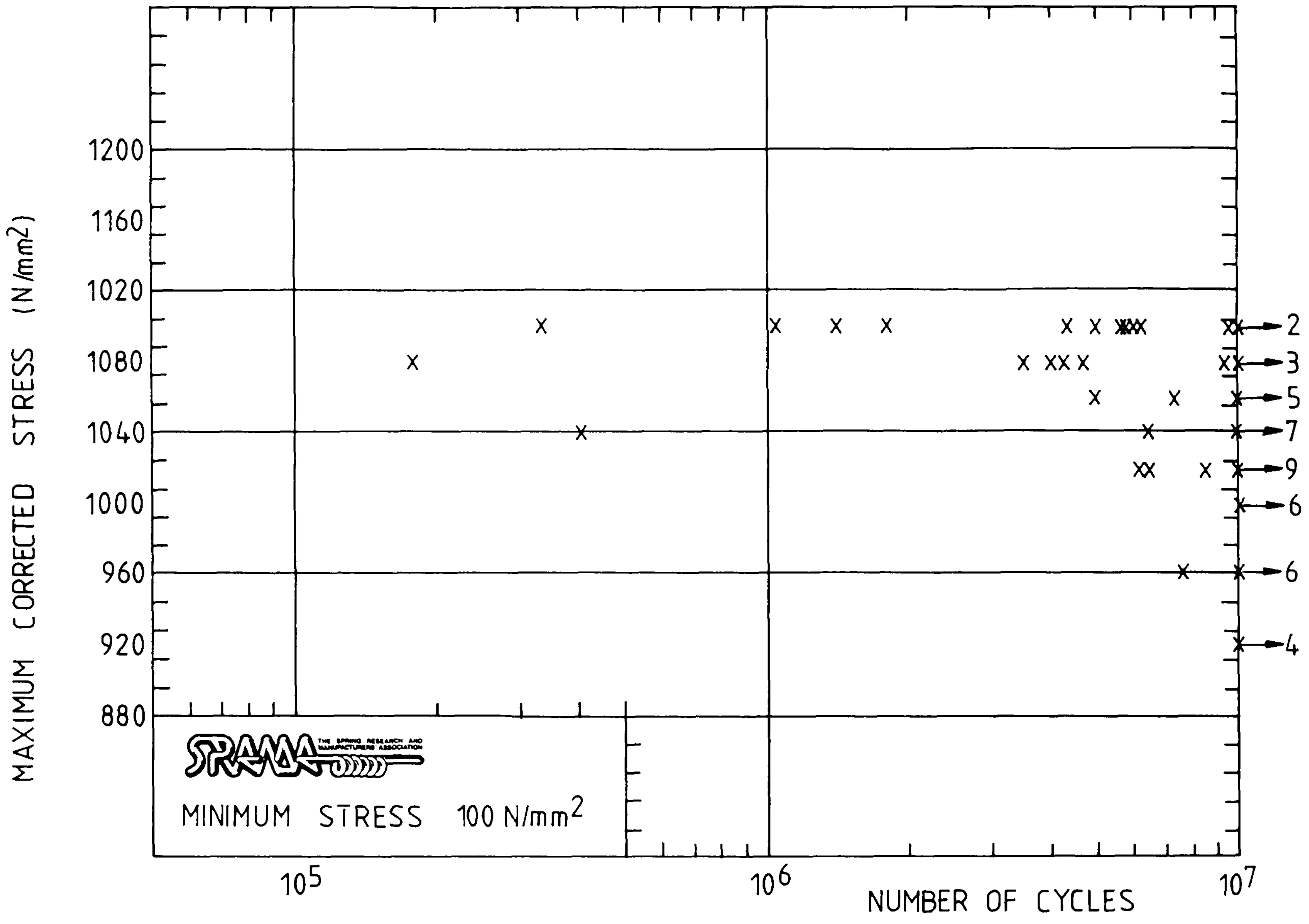

FIG 44. FATIGUE TEST RESULTS: BS 2803 SiC SDF SHOTPEENED.

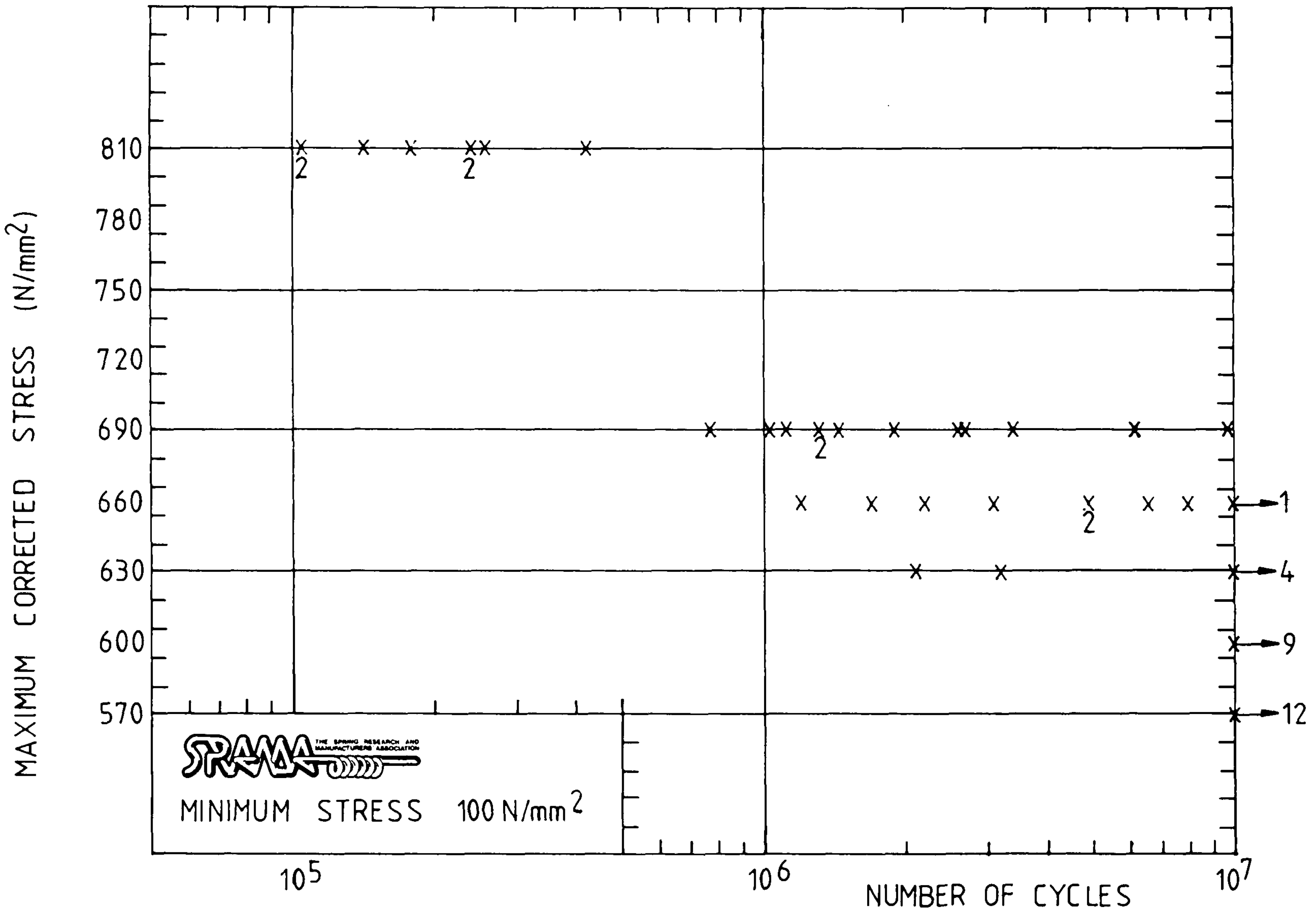

FIG 45. FATIGUE TEST RESULTS: BS 2803 SiC LDF UNPEENED.

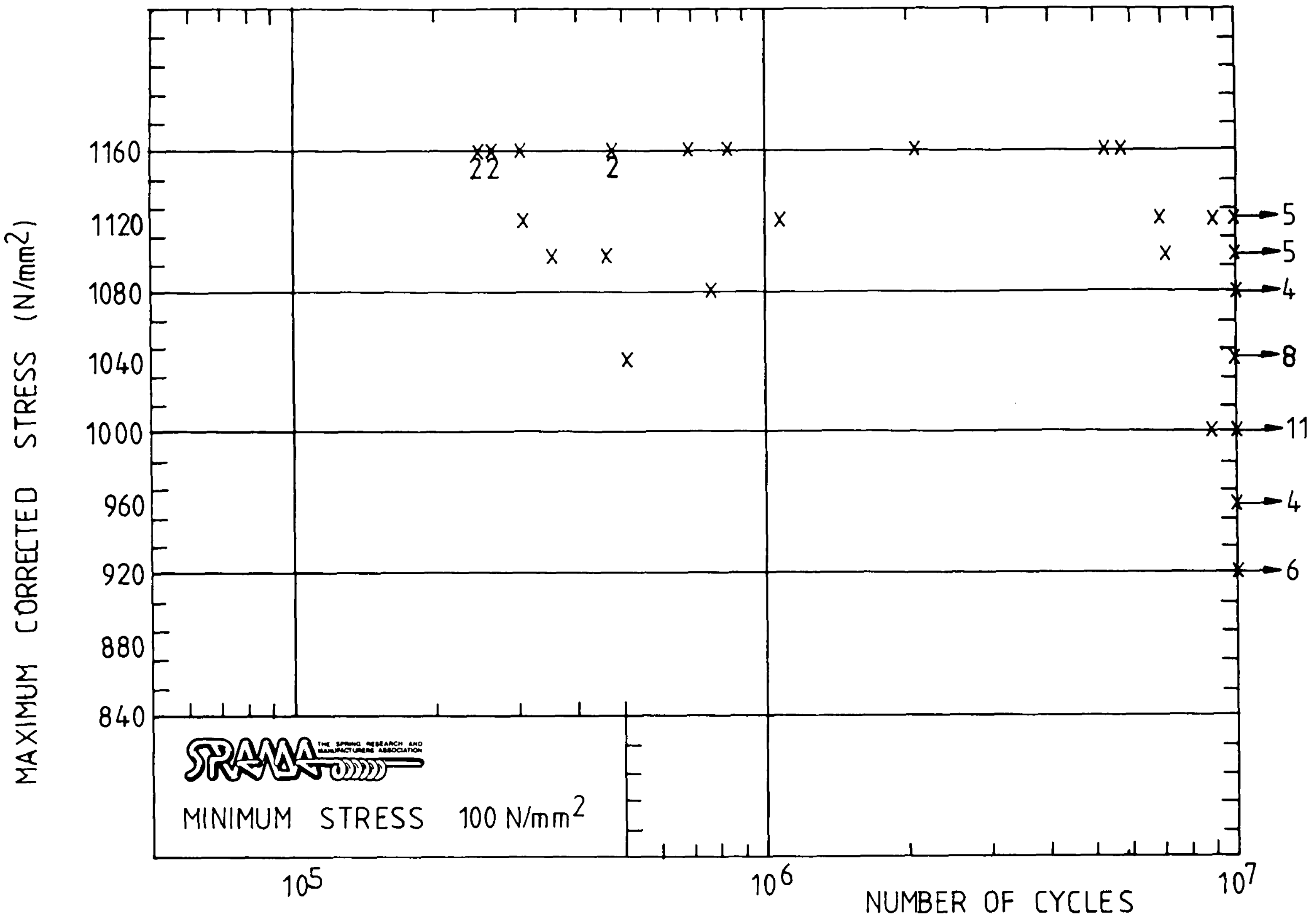

FIG 46. FATIGUE TEST RESULTS: BS 2803 SiC LDF SHOTPEENED.

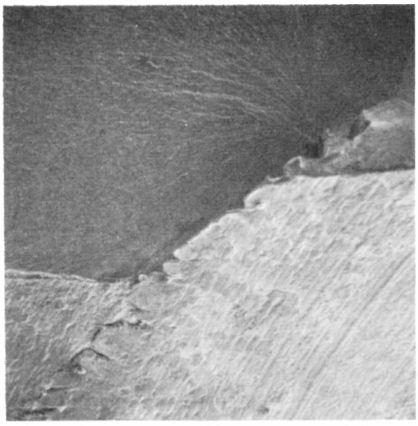

fig 47 x 68

seam in BS 5216 SDF wire
initiating fatigue failure

APPENDIX I

Physical appearance of spring fatigue failures

*by M P Hayes**

During the course of a programme of work aimed at defining the effect of wire defects upon fatigue performance of springs, it was observed that three distinct types of failure occurred. This brief note records these findings.

Materials tested

Three types of spring wire were tested:–

(1) hard-drawn patented carbon steel wire of BS5216 HD type
(2) hard-drawn austenitic stainless of BS2056 302S26 type
(3) hardened and tempered carbon and low-alloy wire, 093 A65 (carbon), 735A50 (1% chrome vanadium) and 685A55 (silicon chrome).

Each of these was coiled into spring in their hardened condition. The strength of BS5216 and BS2056 wires was derived from heavy deformation of the structure during wire drawing. The strength of the BS2803 wire was obtained by hardening and tempering at the final drawn size.

Spring designs, heat treatment and fatigue test method

In order to minimise variables arising from spring designs, the following criteria were employed:–

Wire size	–	2–4 mm diameter
Spring index	–	7
Helix angle	–	7.5°
Number of coils/spring	–	5.5
Number of active coils	–	3.5
Spring ends	–	Closed and ground

All springs were heat treated at low temperature after coiling for 30 min at 375–400°C. Half the springs were shot-peened using grade 230 shot for wire diameter up to 3 mm, and 330 shot for larger wire sizes.

All fatigue tests were carried out on single station forced motion fatigue testing machines designed by The Spring Research and Manufacturers' Association (SRAMA). Failure was detected by the breaking of an electrical circuit of which the spring was a part. Tests were carried out to a maximum of 10 million cycles. Each spring was load tested on SRAMA's electronic load tester prior to fatigue testing, and the stroke of each fatigue test was set to an accuracy of 0.025 mm. The stress in each spring tested could be calculated using the relationship:–

$$\text{Shear stress } \tau = \frac{8PDK}{d^3}$$

where P is the load, D the mean diameter of the coil; d is equal to wire diameter; K is equal to $C + 0.2/C-1$ (= curvature correction factor); $C = D/d$ (= spring index).

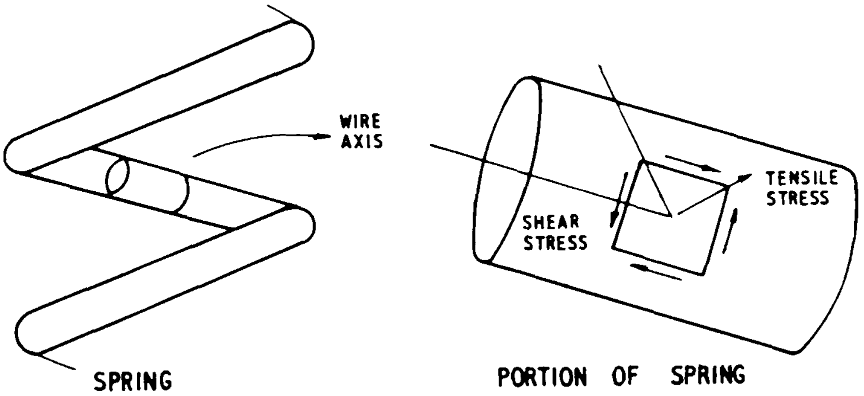

Fig 1. Diagram of stresses in an active coil of a helical compression spring

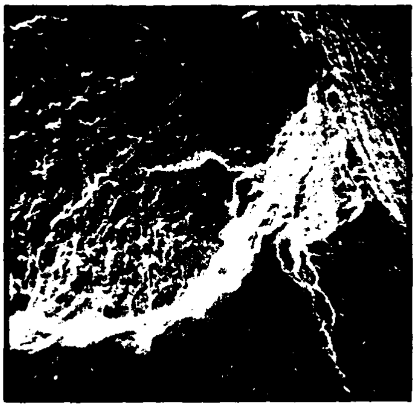

Fig 2. Shear crack parallel to wire axis – BS5216 ND2 of 2.64 mm diameter : range of torsional stress = 560 N/mm^2; number of cycles to failure = 1.2 × 10^6; magnification ×126

Fig 3. Shear crack parallel to wire axis – BS2056 302S26 gr 2 of 2.64 mm : range of torsional stress = 500 N/mm^2; number of cycles to failure = 1.2 × 10^6; magnification ×66

Observations

Each failed spring was identified and viewed on a binocular microscope. The fatigue region of the fracture surface was characterised with respect to its position within the spring. Most failures occurred 1.5 coils from an end and from the inside surface of the spring. Fractures that were damaged or caused by coil to coil fretting were disregarded.

A selection of fatigue surfaces were examined and photographed on SRAMA's Cambridge S4 scanning electron microscope (SEM). Where appropriate, cross-sections were taken from behind the fracture surface, mounted and polished for metallographic examination in order to correlate SEM observations with metallographic structure and defects.

Results

Three distinct types of failure were observed. Reference to the diagram illustrating the stresses in a helical compression spring (Fig 1) will contribute towards an understanding of the definitions of these types of fatigue failure. It should be borne in mind that the stress in a compression spring is essentially torsional. The diagram resolves the torsional stress into shear and tensile components. The tensile stress is at 45° to the plane of the paper, as well as 45° to the surface shear stress.

Failures originating from a shear fatigue crack

In these failures it appears that a shear crack grows normal to the wire surface. The shear crack can be parallel or at right angles to the axis of the wire. After propagating to a depth of between 10 and 150 μm, tensile cracks appear to initiate from either side of the shear crack. The tensile cracks grow to a critical depth after which catastrophic fast fracture occurs. This type of failure is illustrated by photomicrographs (Figs 2–5).

Failures originating from a tensile fatigue crack

The initial shear crack is absent in these failures. Often, the fatigue fracture has multiple origins close to one another on the wire surface. Such fractures are illustrated in Figs 6 and 7.

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*M P Hayes BSc is Head of Materials, The Spring Research and Manufacturers' Association, Sheffield.

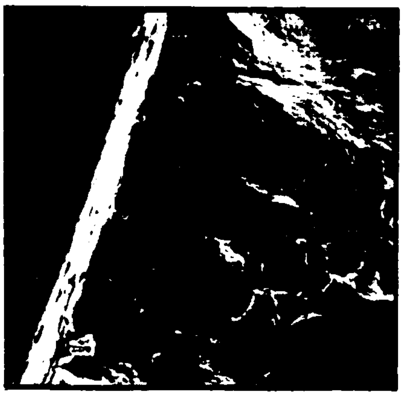

Fig 4. Detail of shear crack – BS2056 302S26 gr 2 of 2.64 mm diameter : range of torsional stress = 450 N/mm^2; number of cycles to failure = 0.9 × 10^6; magnification ×300

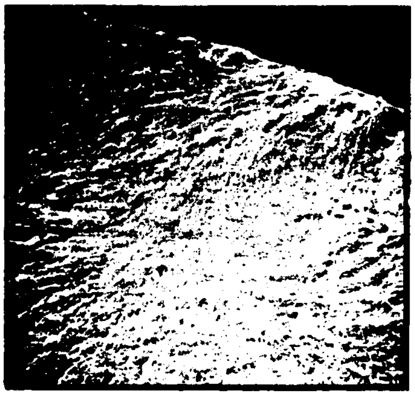

Fig 6. Tensile crack from shot-peened wire surface – BS2803 685A55 gr 2; range of torsional stress = 980 N/mm^2; number of cycles to failure = 0.8 × 10^6; magnification ×156

Fig 8. Failure from inclusion 250 mm below wire surface – BS2803 685A55 gr 2 shot peened; range of torsional stress = 860 N/ mm^2; number of cycles to failure = 7.7 × 10^6; magnification ×144

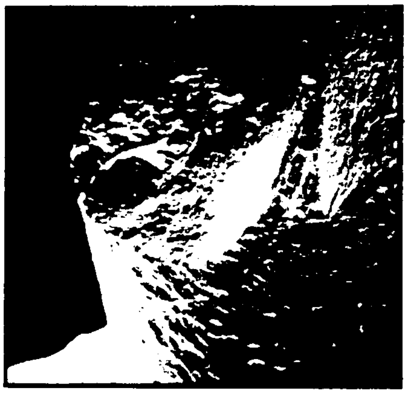

Fig 5. Shear crack transverse to wire axis in shot-peened spring – BS2803 735A56 of 3.66 mm diameter; range of torsional stress = 980 N/mm^2; number of cycles to failure = 0.9 × 10^6; magnification ×33

Fig 7. Tensile cracks from several surface origins – BS2803 735A50 of 4.06 mm diameter; range of torsional stress = 980 N/ mm^2; number of cycles to failure = 0.2 × 10^6; magnification ×84

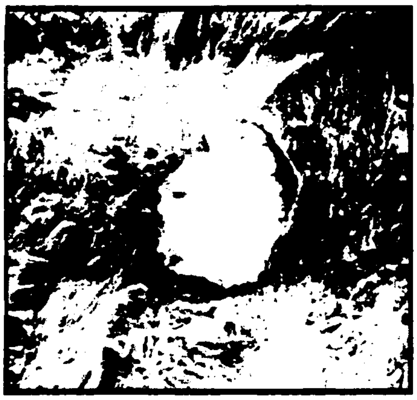

Fig 9. Failure from inclusion 36 μm in diameter – BS2803 685A55 gr 2 shot peened; range of torsional stress = 1020 N/mm^2; number of cycles to failure = 3.1 × 10^6; magnification ×660

Fractures originating sub-surface, invariably from an inclusion

These failures occur only in the hardened and tempered wires and only after shot peening. The size of the inclusion is generally in the 20–40 μm range and its depth below the wire surface is 150–300 μm. Many shapes of inclusions have been observed, two of which are illustrated in Figs 8 and 9.

BS5216 and BS2056 wires

The majority of springs made from hard-drawn wires fail by initiation from a shear-type crack. A minority fail directly from a tensile crack, particularly when the stresses are comparatively high and life of the spring is less than one million cycles. However, when these springs have been shot peened, they generally fail from a tensile crack. Less than 20 per cent of the shot-peened springs showed a shear crack, and this was invariably parallel to the wire drawing direction. No failures have been observed from sub-surface inclusions in hard-drawn wires. This information is summarised in Table 1.

BS2803 wires

The majority of springs made from hardened and tempered wires fail from shear-type cracks. However, the shear cracks have a very different appearance to that seen in the hard-drawn wires. It is possible that the shear crack in some instances is not the initiator of the failure but is merely a connecting link between two tensile fatigue cracks. This is the subject of further metallography at SRAMA.

When hardened and tempered springs are shot peened, the shear cracks are rarely seen. However, some springs do fail from sub-surface inclusions, as shown in Fig 8. The effect of shot peening on the tensile crack which grows from the wire surface can be seen clearly in Fig 6. Again, these observations are summarised in Table 1.

Table 1. Summary of observations for various wire types

Wire type		Failure type		
		Shear	Tensile	Sub-surface
BS5216	As-coiled	75%	25%	0%
	Shot peened	25%	75%	0%
BS2056	As-coiled	100%	0%	0%
	Shot peened	0%	100%	0%
BS2803C	As-coiled	70%	30%	0%
	Shot peened	5%	95%	0%
CrV	As-coiled	100%	0%	0%
	Shot peened	5%	90%	5%
SiCr	As-coiled	95%	5%	0%
	Shot peened	5%	50%	45%

Conclusion

There are three distinct appearances of fatigue failures in springs. These are failures originating from shear-type cracks, from tensile-type cracks and from inclusions.

These observations may enable the establishment of more accurate diagnoses for premature spring failures and possibly they may help the understanding of fatigue failures in other engineering components.

Acknowledgements

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