THE SPRING RESEARCH AND MANUFACTURERS' ASSOCIATION

THE ROOM TEMPERATURE AND HIGH TEMPERATURE FATIGUE AND DYNAMIC RELAXATION PROPERTIES OF HELICAL COMPRESSION SPRINGS MANUFACTURED FROM NIMONIC 90 AND INCONEL X750 WIRES

by

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

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SUMMARY AND CONCLUSIONS

Fatigue tests have been carried out at room temperature on peened and unpeened helical compression springs manufactured from the following nickel based materials:

1. Solution treated and aged Nimonic 90;
2. Hard drawn and aged Nimonic 90 (65% R. of A.); and
3. Cold drawn and aged Inconel X750 (15-20% R. of A.)

Further fatigue tests on unpeened springs have been carried out at a temperature of 400°C.

The tests on unpeened springs at room temperature were carried out at initial stresses of 100 N/mm^2 and 300 N/mm^2; Goodman diagrams have been produced which allow the working stress range to be determined for lives of 10^6 and 10^7 cycles.

The fatigue tests on peened springs at room temperature and on unpeened springs at 400°C were carried out at an initial stress of 100 N/mm^2.

Dynamic relaxation data have been obtained for springs unbroken after 10^7 cycles.

The unpeened fatigue and dynamic relaxation properties have been compared to those of S205, 17-7PH and FV520 (S) stainless steels and the response to shot peening has been contrasted with that of BS 2056 stainless steel and BS 1408M patented cold drawn carbon steel.

It has been concluded that:

1. The room temperature fatigue properties of all the nickel based materials are very similar.
2. All the materials have consistently worse fatigue strengths at room temperature than springs manufactured from S205, 17-7PH and FV520 (S).
3. Shot peening improved the fatigue strengths of all the alloys investigated but the improvement could not be quantified because of the scatter encountered in the data obtained for springs in the shot peened condition.
4. The unpeened fatigue strengths of all the alloys at 400°C are at least equal to the room temperature fatigue strengths; hence the room temperature data can safely be used for design purposes up to 400°C.
5. The dynamic relaxation properties of all the alloys are very good under all the stated test conditions, being in no case greater than 2% and more often less than 1%.

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1. INTRODUCTION

Both Nimonic 90 and Inconel X750 are precipitation hardening nickel based alloys, which contain relatively large additions of chromium to promote good resistance to oxidation at high temperatures.

The nickel based alloys were originally developed for gas turbine application, which demands good creep characteristics of the alloys at high temperatures.

A low creep rate is shown by these alloys for a variety of reasons associated with the basic structure of the materials. In this context, the important factors can be summarised as follows:

1. Structural stability - the alloys retain a face centred cubic crystal structure up to their solidus temperature: hence the large scale movement of atoms associated with many phase changes is completely avoided.

2. Solid solution strengthening - the movement of dislocations generally associated with plastic deformation is made more difficult in these alloys by elements such as cobalt, molybdenum and tungsten, some or all of which are added to the nickel-based alloy.

3. Low stacking fault energy - this feature relates to the extended or partial dislocations encountered in these alloys: effectively it makes it difficult for dislocations to circumvent obstacles, thus preventing their

easy movement through the structure.

4. Grain-boundary pinning - the presence of alloy carbides, such as $Cr_{23}C_6$, at the grain boundaries helps to reduce the possibility of grain boundary sliding, which can occur at high temperatures.

5. Precipitation hardening - this is one of the most influential factors contributing to the high temperature strength of these alloys. The precipitate is generally based on the gamma prime (γ') phase, $Ni_3(Al,Ti)$, which has a lattice parameter very similar to that of the nickel based matrix (<1% mismatch). This results in low interfacial energy values for the coherent precipitate/matrix interface, which effectively increases the stability at high temperatures of the coherent precipitates pinning the dislocations, thus restricting dislocation movement through the structure.

The combination of these factors results in a series of alloys which show a remarkably high resistance to plastic deformation at service temperatures which, with modern gas turbines, may be in excess of $900^{\circ}C$.

In addition to their high temperature creep resistance, however, these alloys possess a good combination of high temperature strength and corrosion resistance, making them suitable materials for springs operating at moderately high temperatures under potentially corrosive conditions. The latter point is especially important in view of certain compounds often encountered in the chemical and petrochemical industries, which may lead to accelerated corrosion or stress-corrosion cracking of the more usual spring materials with the concomitant high losses associated with failure in a highly capital intensive industry.

Previous work reported by the Association(1,2) and elsewhere(3) has dealt with the static stress-relaxation properties of both Nimonic 90 and Inconel X750. The present work was carried out to provide design data for compression springs operating under dynamic conditions of fatigue at room temperature.

A limited amount of work was carried out to assess the response of the springs to shot peening at room temperature (20°C), whilst further work was intended to provide data on the high temperature (400°C) fatigue and dynamic relaxation performance of the alloys.

2. MATERIALS

2.1 Compositions

Nimonic 90 and Inconel X750 wire of diameter 1.63 mm and 2.05 mm respectively was used in the investigation. The Nimonic alloy was obtained in both the solution and hard drawn conditions, the Inconel X750 being supplied in the No. 1 temper condition only (15-20% R. of A).

The nominal analyses of the materials are shown in Table I.

2.2 Spring Design and Manufacture

The springs were coiled on an automatic coiling machine to the designs shown in Table II. The age hardening treatments given to the alloy springs are shown in Table III.

Both the hard drawn Nimonic 90 and the Inconel X750 were age hardened in air circulating tempering furnaces. The solution treated Nimonic 90 was heat treated in a large capacity electrical resistance muffle furnace. The heat treatments were typical of those which would be used for the respective alloys in industry.

The springs were designed to suitable solid stresses calculated from the standard formula:

$$q = \frac{8PDK}{\pi d^3} \qquad \ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad 1$$

where

q = shear stress, N/mm^2

P = load, N

D = mean diameter, mm

d = wire diameter, mm

K = stress correction factor $(c + 0.2)/(C - 1)$

where c = spring index = D/d

A number of the coiled and age hardened springs of each alloy were shot peened simultaneously using S230 shot, to an Almen arc rise of 0.38 A2. All the peened springs were subsequently given a low temperature stress relieving treatment at 250°C/½ hr.

3. EXPERIMENTAL PROCEDURE

3.1 Optical Examination of Aged Springs

Transverse microsections representative of aged springs from each alloy were prepared for examination under the optical microscope. The sections were examined in the unetched condition, and were then etched electrolytically in an aqueous solution of 10% oxalic acid, after which they were re-examined on the microscope.

3.2 Mechanical Testing

Unless otherwise indicated, samples of wire were tested both in the "as received" condition and after the appropriate ageing treatment shown in Table III.

3.2.1 Tensile Testing

The tensile tests were carried out on an Amsler multi-range vertical testing machine incorporating an automatic stress-strain recorder.

An electronic transducer type extensometer, of gauge length 254 mm (10 in), was used in conjunction with the automatic recorder.

As it is very difficult to establish the elastic limit for these materials, the limit of proportionality and the proof stresses were taken as a reasonable guide to the elastic properties of the wires.

3.2.2 Torsion Testing

Most of the torsion tests were carried out using a Tinius-Olsen torsion testing machine with a continuously variable angular velocity of 0-180 degrees/min.

Although this machine had an automatic torque/angular displacement recorder, readings were taken manually throughout each test, so that the results would be amenable to more precise calculation and interpretation by means of regression* analysis.

The solution treated Nimonic 90 proved to be too easily deformed for an accurate determination to be made of the shear properties using the above machine. This material was therefore tested in the un-aged condition using a vertical Amsler torsion testing machine, which was capable of applying torque values of 1130 N.mm (10 lbf in).

In each case torsional stresses and strains were calculated from the relationships:

$$\tau \text{ (torsional stress)} = \frac{d.T}{2\,J} = \frac{16T}{\pi d^3} \quad \ldots\ldots\ldots\ldots\ldots\ldots \quad 2$$

and

$$\phi \text{ (torsional strain)} = \frac{d.\theta}{2\,L} \quad \ldots\ldots\ldots\ldots\ldots\ldots \quad 3$$

where

d = wire diameter, mm

T = applied torque, N.mm

J = second polar moment of area = $\pi d^4/32$

θ = angular displacement radians

L = gauge length, mm > 100d

3.3 Fatigue Testing

3.3.1 Room temperature tests (20°C)

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

Fatigue testing was carried out at initial stresses of 100 N/mm^2 and 300 N/mm^2 on springs in the unpeened condition, and at an intial stress of 100 N/mm^2 only on springs in the peened condition. Each spring was load tested to determine the deflections necessary to give the initial and maximum torsional stresses, the appropriate loads having first been calculated by the transposed statement of equation 1. From the deflections thus obtained, the necessary stroke could be calculated.

3.3.2 High temperature tests (400°C)

These tests were carried out on a forced-motion fatigue machine designed and constructed at the SRAMA. The machine which operates at 48 Hz, is capable of testing springs at temperatures of up to 600°C. The temperature was maintained at a predetermined value by means of a proportional controller, being monitored by means of a chromel/alumel thermocouple extending through the automatic cut-off mechanism into the central region of the testing section. Both the stroke and the minimum lengths were set with the machine at temperature to offset the effects of thermal expansion.

3.4 Dynamic Relaxation

Unbroken springs which survived 10^7 cycles after fatigue testing were re-tested to obtain the maximum load at the original minimum length. The dynamic relaxation, expressed as the percentage loss in load over the original load, was calculated from the results.

3.5 Examination of Fractures

Where possible, all the fractured faces of the broken springs were examined under a low power microscope and the fractures were characterised with respect to mode and appearance.

4. RESULTS

4.1 Microstructural Examination of Aged Springs

Unetched samples

No defects were observed in any of the three alloys examined, although there was evidence of some sub-surface oxidation in the solution treated Nimonic 90 and the cold drawn Inconel X750 to depths of 0.01 mm and 0.04 mm respectively. There was no evidence of surface oxidation in the hard drawn Nimonic 90 section examined.

Etched samples

All the alloys possessed structures consisting of twinned, equiaxed grains of the face centred cubic nickel alloy matrix: the cold worked materials, however, showed some evidence of deformation prior to ageing, in that several of the annealing "twins" deviated from the linear morphology typical of these features.

The solution treated Nimonic 90 showed extensive evidence of a γ' free zone at the surface, the zone extending continuously to a depth of 0.01 mm. There was also ample evidence of γ' denuded zones at the grain boundaries throughout the section.

4.2 Experimental Results

The nominal compositions of the materials investigated are given in Table I.

The spring design data are shown in Table II, and the wire condition and the precipitation hardening treatments given to the coiled springs are recorded in Table III.

The results of the tensile and torsion tests carried out on the wire are given in Tables IV and V respectively.

The appropriate reciprocal values derived from the fatigue data for the unpeened broken springs at room temperature were analysed statistically to give the 50% mean line having the best fit to the results. In the case of ferrous materials, a straight line is often used to represent the limited life data. It is well known, however, that many non-ferrous materials do not exhibit a fatigue limit and hence the fatigue data are better represented by a curve than a straight line. In the present instance, reciprocal relationships were examined and the relationship giving the best fit was selected to represent the data. The relationships were then converted back to a log-linear form and these are shown in the form of S/N curves. In all cases, the correlation coefficients obtained were tested to determine whether they met the minimum acceptable 95% confidence limit.

The S/N curves thus obtained from the data are given in Figs 1 - 3, which also show the maximum recommended working stresses for the springs (85% of solid stress). Springs tested above this stress, however, showed no sign of coil to coil contact. Data extraced from the curves are shown in Table VI and, for comparison purposes, results from work previously carried out at SRAMA on other spring materials are given in Table VII.

Modified Goodman diagrams constructed from the data of Figs. 1 - 3 are shown as Figs. 4 and 5, in which both the mean values and data at the 95% confidence limit are plotted.

The data obtained from the tests on unpeened springs at room temperature are presented in Figs. 6 - 8; relevant mean values from these curves are given in Table VIII, together with some comparative data for other spring materials.

The results of the hot fatigue tests are plotted in Figs. 9 - 11.

Although a full statistical analysis of the data obtained from the results shown plotted in Figs. 6 - 11 has been carried out where possible, it must be appreciated that the tests essentially took the form of 'spot checks' rather than the determination of complete S/N curves. The fatigue data for the shot peened springs of both the solution treated and aged Nimonic 90 and the cold drawn and aged Inconel X750 are shown in Figs. 6 and 8 respectively. In the former case, the scatter of the results was too great to permit a meaningful correlation to be derived, whilst in the latter case insufficient springs were available to provide a basis for correlation.

The dynamic relaxation values of springs which were unbroken after 10^7 cycles are given in Table IX.

Whilst a full fractographic examination was carried out on most of the broken springs, the results are not presented in table form, since much of the data would necessarily have been repetitive in nature. Optical fractographs of typical fracture surfaces are presented as Figs. 12 - 15, however, and the results are considered in detail in the appropriate section of the discussion (Section 6).

5. DISCUSSION

5.1 Effects of Ageing Upon Alloy Properties

In all cases, both the tensile properties and the torsional properties of the alloys were improved significantly by ageing under the recommended time and temperature conditions.

5.1.1 Tensile Properties

The improvement in the tensile properties brought about by ageing can most clearly be seen if the ratio (aged property/unaged property) is considered.

Material	Ratio (aged property/unaged property)			
	L. of P.	$R_{p0.1}$	$R_{p0.2}$	R_m
Nimonic 90 Solution Treated	3.0	2.5	2.4	1.5
Nimonic 90 Hard Drawn	1.4	1.2	1.1	1.1
Inconel X750 Cold Drawn	2.7	1.5	1.4	1.4

The solution treated Nimonic 90 thus shows the greatest improvement in elastic properties, irrespective of whether these are considered as either the proportional limit or the proof stress, The hard drawn Nimonic 90 exhibited the smallest improvement in tensile properties, the cold drawn Inconel X750 being intermediate between the two Nimonic 90 alloys.

Consideration of the (tensile parameter/R_m) ratios emphasises the differing response of the alloys to ageing.

Material	Tensile strength (R_m) N/mm^2	Tensile parameter/R_m ratio		
		L. of P.	$R_{p0.1}$	$R_{p0.2}$
Nimonic 90				
Solution treated	890	0.2	0.4	0.4
Solution treated and aged	1380	0.4	0.6	0.7
Nimonic 90				
Hard drawn	1580	0.5	0.9	0.9
Hard drawn and aged	1810	0.6	0.9	0.9
Inconel X750				
Cold drawn	980	0.3	0.7	0.8
Cold drawn and aged	1340	0.6	0.7	0.8

Ageing thus induced a 100% increase in the proportional limit ratio of the solution treated Nimonic 90, accompanied by a 50% increase in the 0.1% proof stress and a 75% increase in the 0.2% proof stress.

The corresponding changes for the hard drawn Nimonic 90 and the cold drawn Inconel X750 were: 20% (P.L.), 0% ($R_{p0.1}$), 0% ($R_{p0.2}$); and 100% (P.L.), 0% ($R_{p0.1}$), 1% ($R_{p0.2}$) respectively.

Thus it can be concluded that, whilst the solution treated material showed the greatest response to ageing, the cold worked materials exhibited the best elastic properties, both in the aged and the unaged condition.

This behaviour can be understood in terms of modern dislocation and alloy theory, with respect to the dislocation densities and ease of dislocation glide in both solution treated and cold worked alloys, prior to and after precipitation hardening.

5.1.2 Torsional properties

The improvement in torsional properties upon ageing can be seen if the ratio (aged property/unaged property) is considered.

Material	Ratio (aged property/unaged property)		
	L. of P.	0.1% P.S.	0.2% P.S.
Nimonic 90 Solution treated	2.1	1.7	1.8
Nimonic 90 Hard drawn	2.0	1.2	1.2
Inconel X750 Cold drawn	No data available		

Whilst the differences between the ratios for the solution treated and the hard drawn material are not so marked in the case of the torsional properties, as compared to the tensile properties, it is apparent that there is a marked tendency for the solution treated material to show the greatest improvement in properties upon ageing.

More generally, the good torsional properties of the aged materials can be seen if a comparison is drawn between the (torsional parameter/R_m) ratios of the aged alloys and those of materials which could be utilised as alternatives to the nickel based alloys at low to intermediate temperatures e.g. S205, 17-7PH, FV520(S).

Material	Condition	(Torsional parameter/R_m) ratio		
		L. of P.	0.1% P.S.	0.2% P.S.
Nimonic 90	Solution treated and aged 1.63 mm dia.	0.4	0.5	0.5
Nimonic 90	Hard drawn and aged 1.63 mm dia	0.4	0.5	0.6
Inconel X750	Cold drawn and aged 2.05 mm dia	0.4	0.5	0.5
S205 (4)	Cold drawn and LTHT 450°C/2 hrs 1.6 mm dia	0.4	0.5	0.6
17-7PH (5)	Cold drawn and aged 480°C/1 hr 1.6 mm dia	-	0.4	0.5
FV520(S) (6)	Cold drawn and aged 450°C/2 hrs 1.6 mm dia	-	0.6	0.7

This compilation reveals that the (torsional parameter/R_m) ratios of the solution treated Nimonic 90 and the cold drawn Inconel X750 were very similar, the ratio of both these alloys being only slightly lower than similar ratios for the hard drawn Nimonic 90.

5.2 Fatigue Properties

5.2.1 Unpeened springs at room temperature (20°C)

The results given in Table VI appear to indicate that there is little difference in the fatigue performance, other things being equal, for any of the alloys tested.

At each level of initial stress, statistical tests were carried out upon the residuals extracted from the relevant data and the appropriate regression expression used as a control or reference line, to determine if there was any significant difference between the fatigue curves of the three alloys.

Snedecor's 'F' test showed that the residual variances within each initial stress level could be assumed to be independent estimates of the same population variance. The student's 't' test was therefore applicable to ascertain the difference, if any, between the appropriate curves within each initial stress level.

The tests confirmed that, in each case, there was a probability of less than 0.005 that a significant difference between the appropriate curves at any one level of initial stress could arise due to anything other than random chance, i.e. no real significance could be attached to the difference between any of the curves.

A similar trend was apparent in the work reported by Betteridge(7) with respect to the rotating-bending hot fatigue properties of Nimonic 90, 95 and 100 at temperatures of 750°C and 815°C.

Comparison of the limited life fatigue data for the nickel-based alloys (Table VI) with the data for other spring materials (Table VII) shows that springs made from all the nickel based alloys exhibit poorer fatigue properties at room temperature than either S205, 17-7PH or FV520(S) springs manufactured from equivalent diameter wire.

If the fatigue ratios are considered, where the ratio is here defined as fatigue strength for zero initial stress at N cycles/R_m, Table VI shows that the solution treated Nimonic 90 and the cold drawn Inconel X750 have very similar values at both 10^6 and 10^7 cycles. This arises as a result of the close correlation between the fatigue and tensile strengths of the two alloys.

By contrast, the fatigue ratios of the hard drawn Nimonic 90 springs were lower than those of the preceding two alloys, largely because the R_m of the hard drawn alloy was substantially higher than those of the other two alloys, although, as has been demonstrated, there was no significant difference in the fatigue strengths of the alloys considered.

A comparison of the fatigue ratios for 10^7 cycles in Table VI with those for other spring materials in Table VII confirms that the nickel based alloy springs exhibit consistently poorer fatigue properties at room temperature than S205, 17-7PH or FV520(S) springs.

5.2.2 Shot peened springs at room temperature (20°C)

The data for shot peened springs, shown in Figs. 6 - 8, indicate that the fatigue strength of the nickel based alloys investigated can be improved by shot peening. The experimental scatter was greater than that obtained on the unpeened springs, a phenomenon which is often encountered, but not always to this degree, when comparing the fatigue performance of peened and unpeened materials. As a result of this scatter, it was possible to analyse the data for only one of the alloys, the hard drawn Nimonic 90, by the usual statistical techniques.

The reason for the scatter obtained with the results for the shot peened springs is not understood. It is possible, however, that the process of shot peening may remove the oxide film which is responsible for the corrosion resistance of the material. It is doubtful if the beneficial effects of shot peening would be maintained when the springs are used in fatigue applications at high temperatures.

5.2.3 Unpeened springs at 400°C

The results of hot fatigue testing, given in Figs. 9 - 11, show that the fatigue performance at 400°C was not reduced in respect of the room temperature fatigue properties for any of the alloys investigated. This finding was evident even after the initial and maximum stresses were corrected for the reduction in the rigidity modulus at 400°C(8,9), and for the increment of Log life arising as a result of the change in the initial stress.

Whilst it was not possible to derive reliable quantitative data from the spot checks undertaken, it was generally evident that both the Nimonic 90 alloys showed rather better fatigue properties at 400°C than the Inconel X750 alloy. It must be emphasised, however, that in all three alloys, testing at 400°C did not reduce the fatigue properties compared with room temperature values; hence the room temperature fatigue properties at an initial stress of 100 N/mm^2, as exemplified by Figs. 1 - 3, can safely be used as design criteria up to at least 400°C. A similar conclusion was reached by Gray(10) in his investigation into the fatigue properties, at 250°C, of S205, 17-7PH and FV520(S) spring materials.

5.3 Dynamic Relaxation Behaviour

From the data given in Table IX, it is apparent that none of the unpeened springs tested at room temperature showed any relaxation after 10^7 cycles at an initial stress of 100 N/mm^2. Furthermore, only Inconel X750 showed any relaxation at the higher initial stress of 300 N/mm^2. In this case, the value of 2.0%, although the highest obtained in all the present series of tests, was still very low in comparison with the degree of relaxation which can be tolerated in many applications.

The relaxation of the shot peened Nimonic 90 springs varied from 0.5% to 0.8%. It can be seen that the lower value was obtained for the solution treated Nimonic 90, operating at the higher level of maximum stress, hence indicating that this alloy possessed the best resistance to dynamic relaxation after peening.

Whilst no data were available for the dynamic relaxation of the shot peened Inconel X750 springs, it is to be expected that the material would exhibit some relaxation after peening. It is thought unlikely that the relaxation would differ significantly from the results obtained for the hard drawn Nimonic 90 alloy.

The dynamic relaxation of the springs tested at 400°C varied from 0.3% for the Inconel X750 to 0.7% for both the Nimonic 90 alloys.

At these levels of relaxation, and bearing in mind that the value for the Inconel springs was obtained at the significantly lower maximum stress of 500 N/mm^2 compared with the stress levels of 550 - 600 N/mm^2 for the Nimonic 90 alloy, it is probably safe to say that the relaxation behaviour of all the alloys was of a similar order, at a value of less than 1%, when tested at 400°C. The relaxation behaviour of these alloys compares very favourably with that of S205, 17-7PH and FVS20(S) at 250°C(10).

6. EXAMINATION OF FRACTURES FROM BROKEN SPRINGS

6.1 Unpeened Springs Tested at Room Temperature (20°C)

The fractures could be broadly divided into two categories, which appeared to be largely characteristic of the particular alloy concerned.

Solution treated Nimonic 90 - Fracture in these springs usually initiated at the inside, most highly stressed, region of the coil, the resulting shear crack transforming to the 45° helicoidal mode along the planes of maximum tensile stress. These two fracture zones generally occupied 30 - 90% of the total fracture surface. Final fracture invariably occurred in transverse shear, this portion of the fracture very often giving the appearance of cleavage, with many bright, crystal "facets" in evidence (Fig. 12).

Upon closer examination, however, many widely spaced conchoidal markings could be seen in this "facetted" zone. This would imply that a significant proportion of the zone would have resulted from intermittent rapid growth of the fatigue crack, culminating in the final shear fracture as a result of stress overload.

Hard Drawn Nimonic 90 and Cold Drawn Inconel X750 - These two alloys were very similar, in that about 75% of the springs from each alloy fractured completely in the transverse shear mode, giving a very flat fracture surface. These fractures consisted of two zones, namely a dull, fine grained transverse shear zone strongly resembling a fatigue crack and an area of "facetted" fracture which was once again strongly reminiscent of a cleavage type failure (Fig. 13). Fracture in these springs invariably initiated on the outside region of the coil. It was interesting to note that, in some of these springs which failed in the transverse shear mode, longitudinal cracking had occurred along the length of the spring on the outside of the coil. Microscopical examination of a transverse section of a cracked spring showed that the crack penetrated into the wire to a depth of 0.18 mm. Furthermore, no oxidation was evident, indicating that cracking had occurred after ageing, i.e. during testing. It will be remembered that the microsections taken from the original samples of aged wire showed no evidence of surface cracking.

The remaining 25% of fractures were initiated on the inside regions of the coil and exhibited the combined transverse shear/ 45° helicoidal tensile fracture previously described. This mode of fracture did not appear to be influenced by either the initial stress or the maximum stress levels, being generally distributed throughout the series of tests on both alloys.

In both these two modes of fracture, the dull, fine grained transverse shear/45° tensile zone occupied about 20% - 60% of the fracture surface, with the greater proportion in the springs tested at the lower values of maximum stress. At first glance, therefore, the fatigue zone of the fracture in these alloys appeared to form a smaller proportion of the total fracture than that observed for the solution treated Nimonic 90 springs. As previously mentioned, however, the fatigue zone could have extended into the "facetted" portion of the fracture.

6.2 Shot Peened Springs Tested at Room Temperature (20°C)

The fractures of the broken springs from all three alloys were virtually identical in appearance, fracture initiating about 0.1 - 0.15 mm below the surface, on the outside region of the coil.

All the fractures were in the transverse shear mode, with occasional regions of longitudinal shear, and consisted of a dull, fine grained zone associated with the initiation point followed by the bright, "facetted" zone previously observed in the unpeened springs (Fig. 14). A fine grained annular region was present to a depth of 0.1 - 0.15 mm in some of the Nimonic 90 springs but was much less in evidence in the Inconel X750 springs.

The major difference in fracture appearance in the shot peened springs from each alloy lay in the relative proportions of the dull, fine grained and the bright "facetted" regions of the surface. In both the solution treated Nimonic 90 and the cold drawn Inconel X750 springs, the proportion of the dull, fine grained zone tended to increase as the maximum stress decreased. The hard drawn Nimonic 90 was unusual, however, in that the trend was reversed, with the fine grained zone decreasing in proportion as the maximum stress decreased. Whilst the reasons for this behaviour are obscure at the moment, the observation would seem to corroborate the finding that the improvement in fatigue strength of the hard drawn Nimonic 90 springs in the peened condition tended to decrease as the maximum stress decreased. Further investigation, possibly involving scanning electron microscopy of the fracture surfaces, would be necessary to clarify these points and to gain an understanding of the factors contributing to this aspect of the difference in fatigue and fracture behaviour of the various alloy springs after shot peening.

6.3 Unpeened Springs Tested at 400°C

Solution treated Nimonic 90 - The fracture appearances of these springs were similar in almost all respects to those reported for the springs broken at room temperature (Section 6.1) consisting of initiation at the inside of the coil, followed by a 45° helicoidal tensile zone with the final fracture in a "facetted" region of transverse shear. At 400°C, however, the proportion of 45° helicoidal tensile fracture was reduced to about half that observed during the room temperature tests, whilst the amount of "facetted" transverse shear leading to final fracture was increased.

Hard drawn Nimonic 90 and cold drawn Inconel X750 - The fracture appearances of both these alloys, tested at 400°C, were very similar, consisting of a bright "facetted" zone preceded by a dull, fine grained fracture which had propagated from the initiation point at the outside of the coil (Fig.15).

The main difference between the two alloys lay in the relative proportions of the two zones, the dull, fine grained zone generally comprising about 10% of the fracture in the Inconel X750 but about 40-60% of the fracture in the Nimonic 90.

6.4 Comments on Fracture Mechanisms

It is apparent from the foregoing observations that the fractures of unpeened springs taken both at room temperature and at 400°C could be divided into two distinct categories, i.e. a combined 45° helicoidal tensile/transverse shear "facetted" fracture associated with the solution treated Nimonic 90, and a 100% transverse shear failure, which still showed the "facetted" appearance and which was associated with both of the cold worked alloys. Furthermore, shot peening of the springs resulted in all the alloys failing completely in the transverse shear mode.

An observation which may be of some significance was that, without exception, all the completely transverse shear factures were associated with crack initiation at the outside of the coil, whilst the 45° tensile fractures were all initiated from the inside of the coil. Whilst it is difficult to separate cause and effect in the present case, it is known that certain nickel based alloys may prove difficult to coil(3) because of their poor frictional qualities. The sensitivity of the alloy to the coiling technique may thus have played a part in the fracture of those springs exhibiting complete transverse shear failure. Evidence for this could be seen in the broken springs of hard drawn Nimonic 90, some of which had cracked longitudinally along the outside of several coils. These cracks could have been associated with the surface damage resulting from the sliding action of the coiling points during manufacture of the spring. Further work would be necessary to clarify the mechanism involved.

The "facetted" transverse shear regions of the fractures observed in the present work appeared to correspond with the fractures observed by Gell and Leverant(11). They investigated the fracture mechanisms operative in a heat treated nickel based superalloy similar to Inconel X750. Although their tests were carried out in pulsating tension, the fractures encountered were very similar to those found in the present work, consisting of "facetted cleavage" fatigue surfaces. After examination of the surfaces by scanning electron microscopy and X-ray diffraction techniques, they concluded that growth of the fatigue crack had occurred by a mechanism involving intense local slip on the {111} planes, in the <110> directions of the alloy, i.e. in the close packed planes and directions of the face centred cubic structure, which exhibits the lowest value of critical resolved shear stress. They further concluded that the bright, facetted fatigue zone occupied up to 75% of the fracture area, the presence of micro-striations suggesting that the cleavage type failure had occurred over millions of cycles rather than in the catastrophic manner normally associated with this mode of fracture.

Whilst the optical appearance of the fractures found in the present work is to some extent in accordance with these conclusions, the interpretation of Gell and Leverant does not explain why the solution treated Nimonic 90 fractured initially in the 45° tensile mode, before final fracture in the transverse shear mode.

It is known, however, that a significant proportion of the carbon in solution treated and aged Nimonic 90 exists at the grain boundaries in the form of $Cr_{23}C_6$ type chromium carbides(12). The formation of this chromium rich carbide reduces the proportion of chromium in the alloy matrix immediately adjacent to the grain boundary. This, in turn, increases the solubility of the γ', Ni_3 (Al, Ti) phase, which is responsible for precipitation hardening in this alloy, resulting in a γ' denuded zone also adjacent to the grain boundary. It will be recollected that microscopic examination of the alloys showed, in fact, that the solution treated and aged Nimonic 90 springs did indeed contain extensive zones of γ' denudation at the grain boundaries.

It is possible that tensile fracture occurred in this alloy as a result of interfacial fracture and void formation at the interface between the hard $Cr_{23}C_6$ "inclusions" and the adjacent, comparatively soft γ' denuded matrix. This would arise when the stress concentration of the original shear crack had increased the tensile stress to a point at which tensile failure became the favoured mechanism of crack growth.

It is well established that tensile failure is initiated primarily by interfacial separation occurring at hard second phase particles, effectively leading to a reduction in the load bearing cross-sectional area normal to the tensile force.

This mode of failure usually requires intense local slip and plastic deformation and would therefore be expected to occur over a period of time, the fatigue crack "jumping" from void to void. It is possible, therefore, that the tensile fracture formed in this way over an extended period of time, by the formation and interlinking of voids nucleated at the grain boundary carbide particles.

At a later stage of fracture, when the crack would be tending to propagate more rapidly because of the increased stresses, the lack of time available for tensile separation and void nucleation would possibly have led to the crack reverting to the transverse shear mode, which was always observed at the area of final fracture of the spring.

Although the mechanism suggested may go some way towards explaining why the solution treated Nimonic 90 fractured in such a complex manner, it does not explain why the alloy always fractured completely in transverse shear after shot peening. The work hardening effect at the surface may be of some significance here, especially in view of the fact that the hard drawn Nimonic 90 always tended to favour this fracture mode.

The exact cause of this behaviour is not yet known; further, detailed investigation of the fracture mechanisms would be necessary to provide explanations for the various complex phenomena observed in the present work.

7. CONCLUSIONS

1. In terms of the improvement in mechanical properties, the solution treated Nimonic 90 showed the greatest response to ageing, followed by the Inconel X750 and the hard drawn Nimonic 90 in that order. The hard drawn Nimonic 90 alloys, however, exhibited the best elastic properties after ageing.
2. The torsion properties of the hard drawn and aged Nimonic 90 were superior to those of other materials and conditions investigated.
3. The room temperature fatigue properties of the alloys were all very similar for each of the two initial stress levels employed.
4. The nickel based alloys investigated all exhibited fatigue properties at room temperature which were consistently poorer than the equivalent properties for S205, 17-7PH and FV520(S) springs manufactured from wire of equivalent diameter (i.e. 1.6 mm).
5. Shot peening improved the room temperature fatigue properties but the scatter encountered did not permit the degree of improvement to be quantified.
6. The fatigue strengths at 400°C of all the alloys investigated were at least equal to their room temperature fatigue strengths. The room temperature fatigue data can, therefore, be used as design data for temperatures up to at least 400°C.

7. The dynamic relaxation properties after 10^7 cycles of all the alloys were very good under all the conditions investigated, being in no case greater than 2% and generally less than 1% in magnitude, even at 400°C.

8. The fracture behaviour of the alloys was complex, although easily discernable in optical appearance. The types of fracture observed could be broadly classified according to the condition of the particular alloy concerned.

8. RECOMMENDATIONS

1. Whilst the present work outlines the room temperature and high temperature fatigue behaviour of the nickel based alloys under normal atmospheric conditions, it would be desirable to follow up the work with tests carried out under conditions of corrosion-fatigue, since the alloys may be expected to operate in this mode.

2. Investigations of the hot fatigue properties should be extended up to higher temperature, e.g. 600°C. The dynamic relaxtion properties, in particular, are likely to be adversely affected at higher temperatures.

3. The effect of shot peening on these alloys should be further investigated.

4. The influence of coiling technique upon crack initiation in the cold drawn alloys could usefully be investigated. The effects of wire lubricant upon coiling behaviour, for example, may be important.

9. REFERENCES

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TABLE 1 INVESTIGATED CHEMICAL COMPOSITIONS OF MATERIALS

ELEMENT %	NIMONIC 90	INCONEL X750
Carbon	0.13	0.08
Manganese	1.0	1.0
Silicon	1.5	0.5
Chromium	18-21	14-17
Nickel	Balance	70 min
Copper	-	0.5
Iron	5.0	5.0-9.0
Aluminium	0.8-2.0	0.4-1.0
Titanium	1.8-3.0	2.0-2.5
Cobalt	15-21	1.0
Niobium + Tantalum	-	0.7-1.2

TABLE II SPRING DESIGN DATA

SPRING PARAMETERS	NIMONIC 90		INCONEL X750
	SOLUTION TREATED	HARD DRAWN (65% RA)	COLD DRAWN (15-20% RA)
Wire Diameter, mm.	1.63	1.63	2.05
Mean Coil Diameter, mm.	13.11	13.23	14.80
Free Length, mm. (Pre-stressed)	28.58	30.58	29.62
Active Coils	5.5	5.5	5.5
Total Coils	7.5	7.5	7.5
Solid Stress, N/mm^2 (calculated from load tests).	750	920	730
Ends	Closed and ground	Closed and ground	Closed and ground

TABLE III WIRE CONDITION AND SPRING HEAT TREATMENTS

MATERIAL	WIRE CONDITION	SPRING HEAT TREATMENTS
Nimonic 90	Solution Treated 1080°C./1h.A.C.	Aged 750°C./4h.A.C.
Nimonic 90	Hard drawn, Spring Temper (65% R.A.)	Aged 650°C./4h.A.C.
Inconel X750	Cold drawn No. 1 Temper (15-20% R.A.)	Aged 730°C./16h.A.C.

TABLE IV

TENSILE PROPERTIES

MATERIAL	WIRE CONDITION	TENSILE STRENGTH Rm (N/mm^2)	LIMIT OF PROPORTIONALITY (N/mm^2)	PROOF STRESS (N/mm^2)		REDUCTION IN AREA %	ELONGATION %
				Rp 0.1	Rp 0.2		
Nimonic 90 Solution Treated	Solution treated, as received. (3)*	890	190	360	390	60	43
	Aged 750°C/4 h (3)	1380	580	900	940	40	20
Nimonic 90 Hard drawn, 65% R.A.	Hard drawn, as received. (2)	1580	740	1410	1480	32	-
	Aged 650°C/4 h (3)	1810	1020	1640	1700	25	3
Inconel X750, Cold drawn, 15-20% R.A.	Cold drawn, as received. (2)	980	290	670	750	70	25
	Aged 730°C/16 h	1340	800	990	1040	39	11

* Figures in parentheses refer to number of samples used to obtain mean results given.

TABLE V

TORSIONAL PROPERTIES

MATERIAL	WIRE CONDITION	LIMIT OF PROPORTIONALITY (N/mm^2)	PROOF STRESS, (N/mm^2)		MODULUS OF RIGIDITY, G. (N/mm^2)
			0.1%	0.2%	
Nimonic 90, Solution treated	Solution treated, as received. (2)*	240	370	380	8.1×10^4
	Aged 750°C/4 hrs. (3)	510	640	690	8.7×10^4
Nimonic 90, Hard drawn, 65% R.A.	Hard drawn, as received. (2)	390	800	870	7.4×10^4
	Aged 650°C/4 hrs. (2)	770	960	1020	8.4×10^4
Inconel X750, Cold drawn 15-20% R.A.	Cold drawn, as received.		NO RESULTS AVAILABLE		
	Aged 730°C/16 hrs. (2)	500	620	660	7.6×10^4

* Figures in parentheses refer to number of samples used to obtain mean results given.

TABLE VI FATIGUE DATA FOR UNPEENED HIGH NICKEL ALLOY SPRINGS

MATERIAL	MATERIAL CONDITION	R_m (N/mm^2)	LIFE CYCLES	FATIGUE STRENGTH (N/mm^2) AT INITIAL STRESS LEVEL (N/mm^2)			FATIGUE RATIO AT ZERO INITIAL STRESS
				0	100	300	
Nimonic 90	Solution treated and aged	1380	10^6	430	510	680	0.31
			10^7	230	325	490	0.17
Nimonic 90	Hard drawn and aged	1810	10^6	420	510	645	0.23
			10^7	240	330	530	0.13
Inconel X750	Cold drawn and aged	1340	10^6	400	490	660	0.30
			10^7	260	350	550	0.19

TABLE VII COMPARATIVE FATIGUE DATA FOR SOME UNPEENED SPRING MATERIALS

MATERIAL	MATERIAL CONDITION	R_m (N/mm^2)	LIFE CYCLES	FATIGUE STRENGTH (N/mm^2) AT INITIAL STRESS LEVEL (N/mm^2)			FATIGUE RATIO AT ZERO INITIAL STRESS
				0	100	300	
S205 [4]	1.6 mm dia. wire, hard drawn. L.T.H.T. 450°C/ 2 h	1630	10^6	-	-	-	-
			10^7	590	650	790	0.36
17-7 PH [5]	1.6 mm dia. wire, hard drawn. Aged 480°C/1 h	1830	10^6	-	-	-	-
			10^7	540	630	820	0.29
FV520(S) [6]	1.6 mm dia. wire, hard drawn. Aged 450°C/2 h	1750	10^6	700	790	920	0.40
			10^7	470	570	760	0.27

TABLE VIII FATIGUE PROPERTIES OF PEENED AND UNPEENED SPRINGS AT AN INITIAL STRESS OF 100 N/mm^2

MATERIAL	WIRE DIAMETER (mm)	WIRE CONDITION	SPRING HEAT TREATMENT	SURFACE CONDITION	FATIGUE STRENGTH, (N/mm^2), AT	
					10^6 CYCLES	10^7 CYCLES
Nimonic 90	1.63	Solution treated.	Aged 750°C/4 h	S/P [a] U/P	- 510	- 325
Nimonic 90	1.63	Hard drawn,	Aged 650°C/4 h	S/P [a] U/P	720 510	- 330
Inconel X750	2.47	Cold drawn, 15-20% R.A.	Aged 730°C/16 h	S/P [a] U/P	- 490	- 350
BS2056 (13) (EN 58A)	1.22	Hard drawn, 50-60% R.A.	L.T.H.T. 450°C/2 h	S/P [b] U/P	840 750	820 600
BS1408M (13) (R2)	1.63	Patented, hard drawn	Stress relieved 350°C/½ h	S/P [b] U/P	1130 940	920 725

[a] Shot peened 0.38 A2; stress relieved 250°C/½ h

[b] Shot peened 0.28/0.30 A2; stress relieved 220°C/½ h.

TABLE IX DYNAMIC RELAXATION PROPERTIES OF NICKEL ALLOY SPRINGS UNBROKEN AFTER 10^7 CYCLES

SPRING MATERIAL	TEST TEMPERATURE	SPRING CONDITION	INITIAL STRESS (N/mm^2)	MAXIMUM STRESS (N/mm^2)	CYCLES ENDURED	DYNAMIC RELAXATION %
Nimonic 90, solution treated and aged 750°C/4 h	R.T.(20°C)	U/P			No data available	
	R.T.(20°C)	U/P	300	515	2×10^7	0
	R.T.(20°C)	S/P	100	550	1.82×10^7	0.5
	R.T.(20°C)	S/P	100	525	1.42×10^7	0
	400°C.	U/P	100	600*	1.6×10^7	0.7
Nimonic 90, Hard drawn and aged 650°C/4 h	R.T.(20°C)	U/P	100	330	2×10^7	0
	R.T.(20°C)	U/P	300	580	2.03×10^7	0
	R.T.(20°C)	S/P	100	505	1.22×10^7	0.8
	400°C.	U/P	100	550*	1.3×10^7	0.7
Inconel X750, Cold drawn and aged 730°C./16 h	R.T.(20°C)	U/P	100	420	1.01×10^7	0
	R.T.(20°C)	U/P	300	520	1.17×10^7	1.9
	R.T.(20°C)	S/P			No data available	
	400°C.	U/P	100	500*	1.23×10^7	0.3

* Room temperature stress, not corrected for change in 'G' at 400°C.

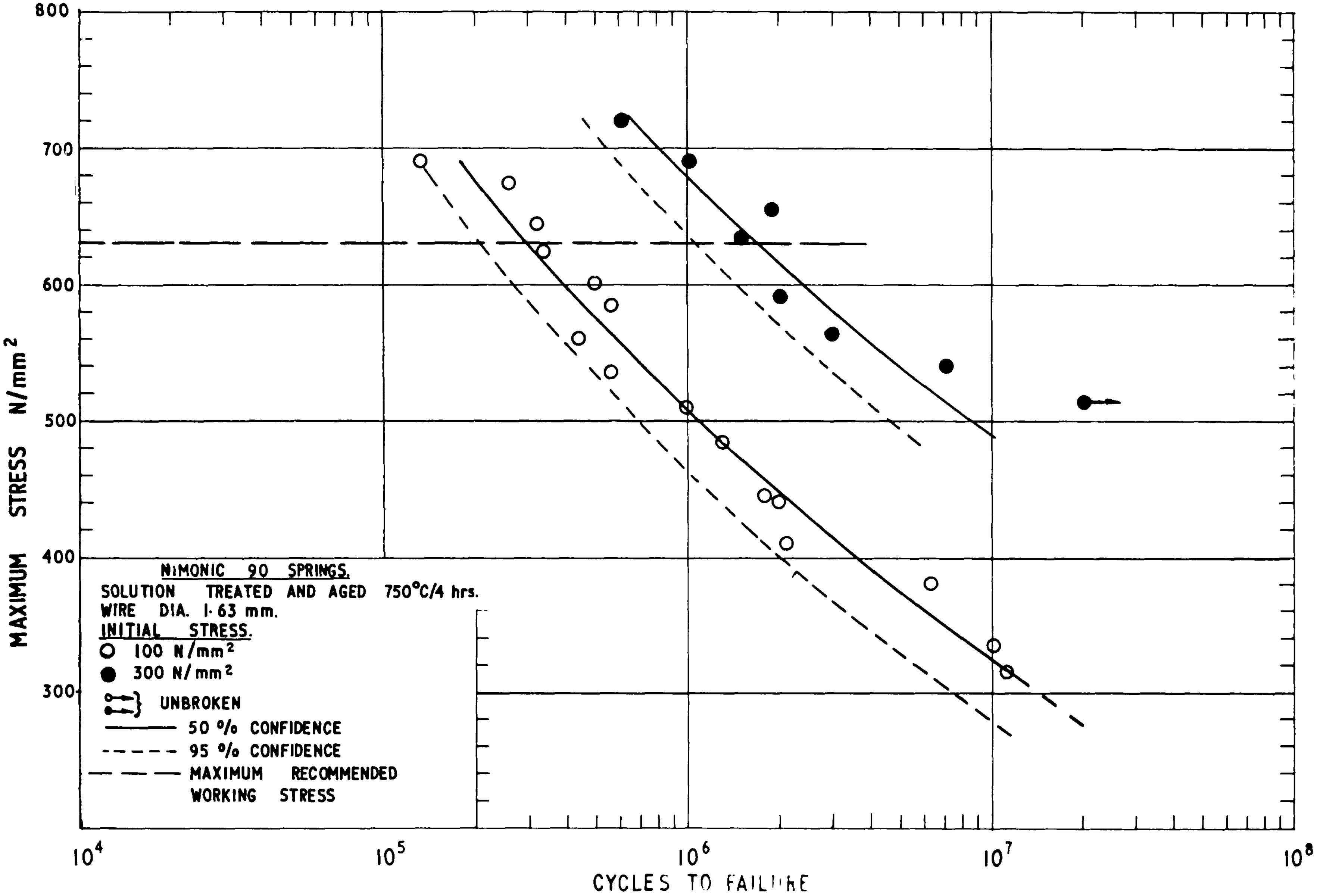

FIG. I S/N CURVES FOR UNPEENED SPRINGS OF SOLUTION TREATED NIMONIC 90.

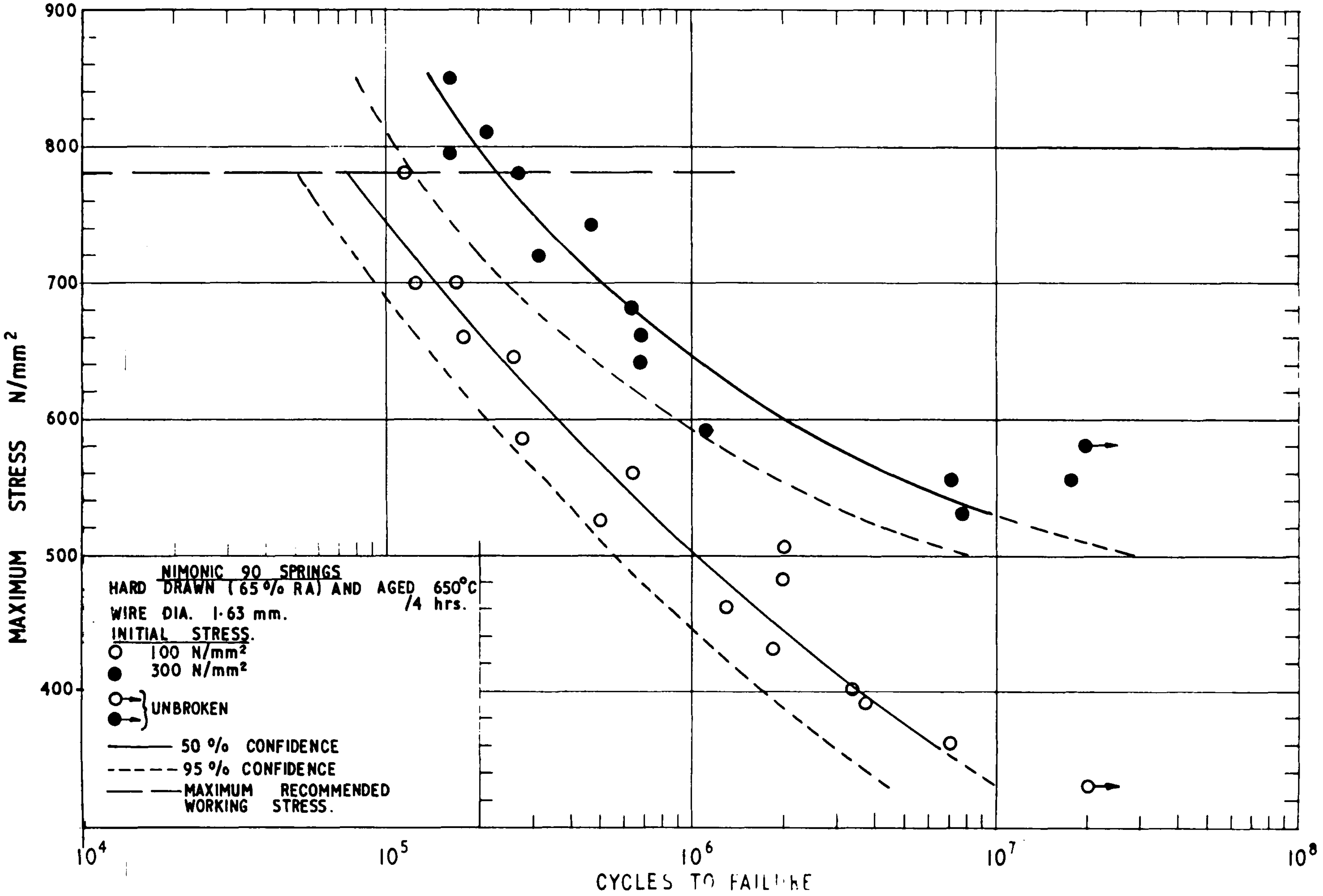

FIG. 2 S/N CURVES FOR UNPEENED SPRINGS OF HARD DRAWN NIMONIC 90.

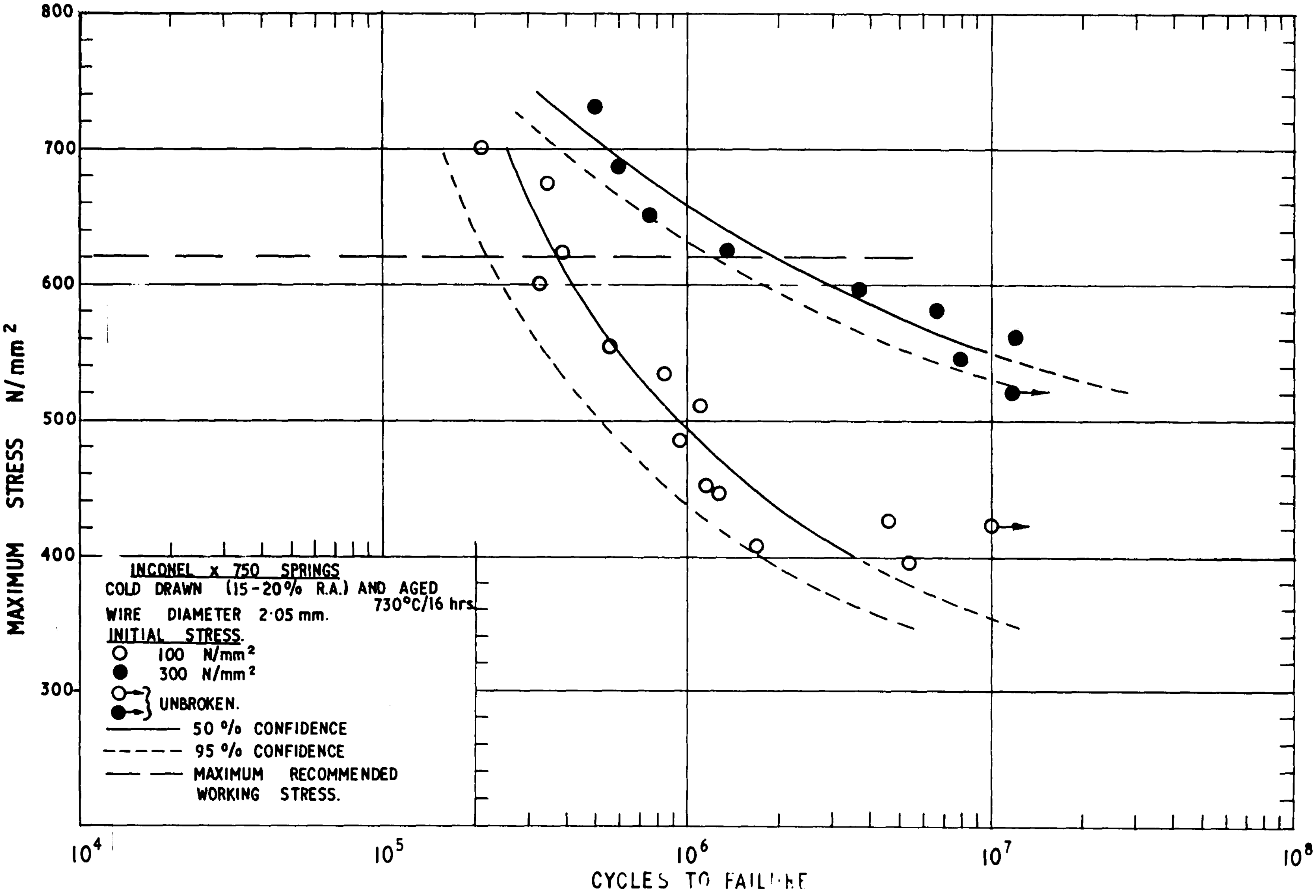

FIG. 3 S/N CURVES FOR UNPEENED SPRINGS OF COLD DRAWN INCONEL x 750.

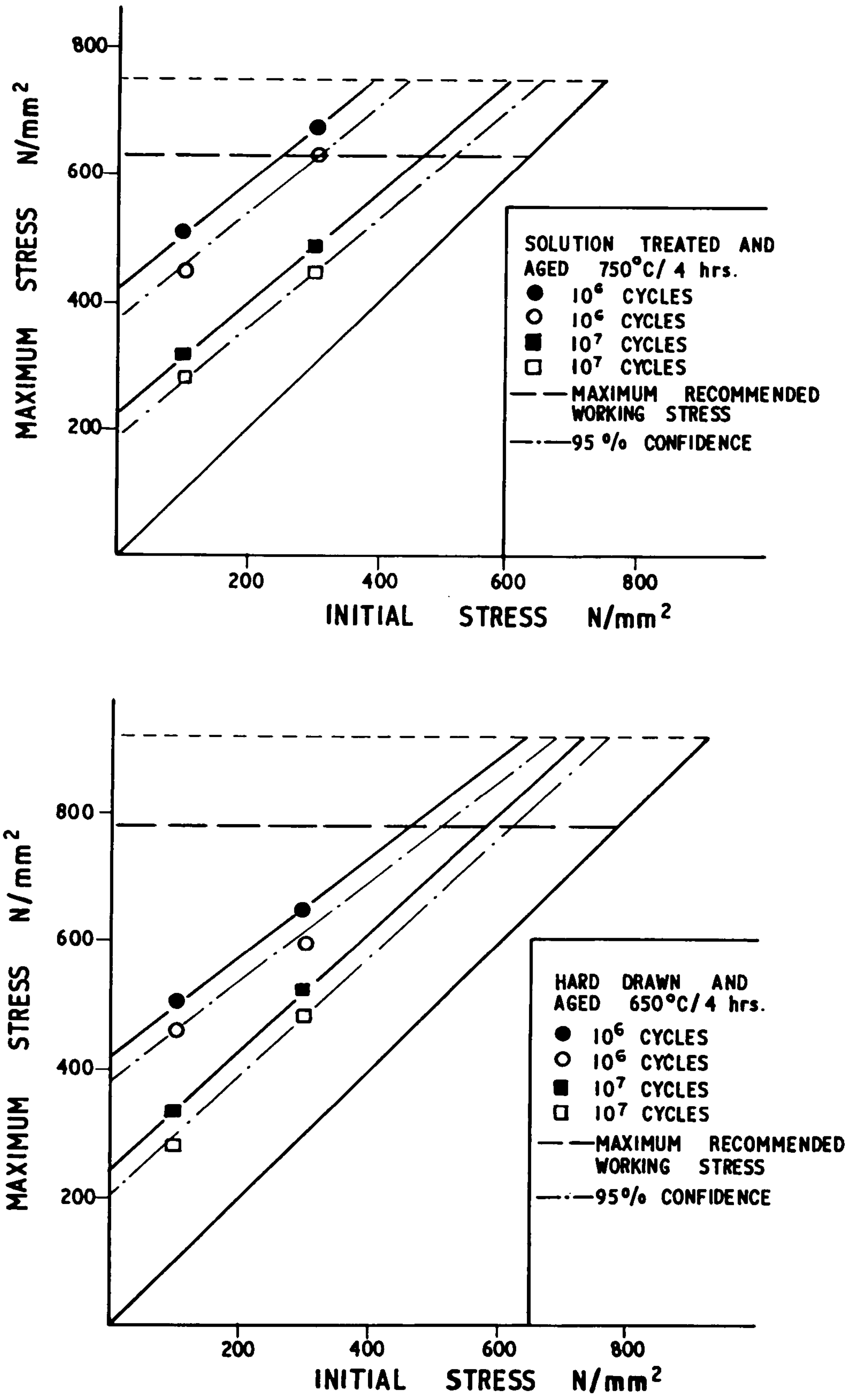

FIG. 4 MODIFIED GOODMAN DIAGRAMS FOR NIMONIC 90 COMPRESSION SPRINGS (UNPEENED)

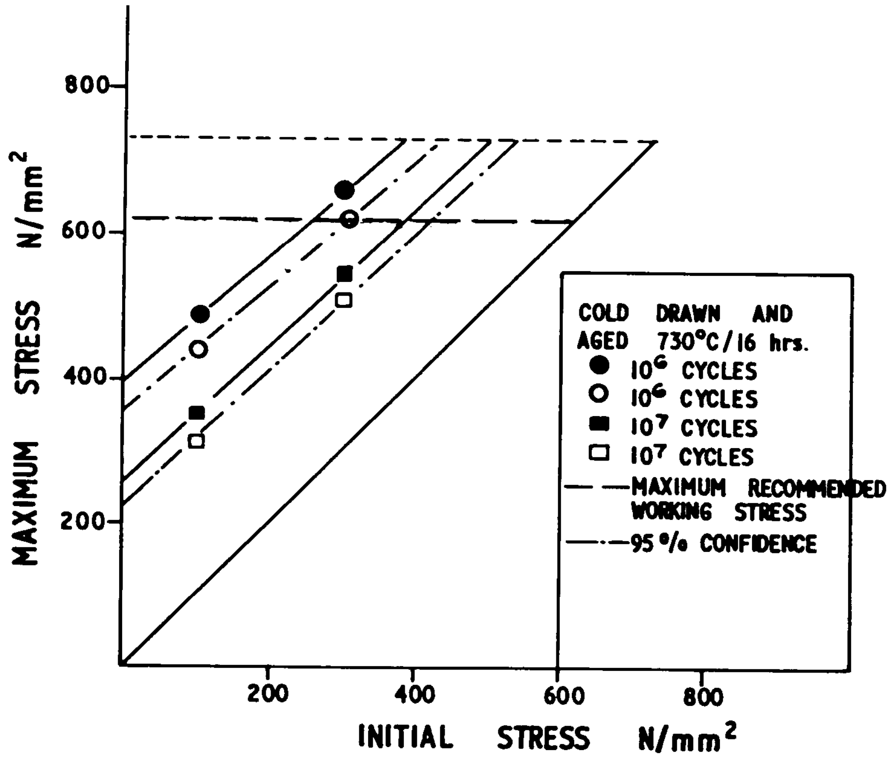

FIG. 5 MODIFIED GOODMAN DIAGRAM FOR INCONEL x 750 COMPRESSION SPRINGS (UNPEENED)

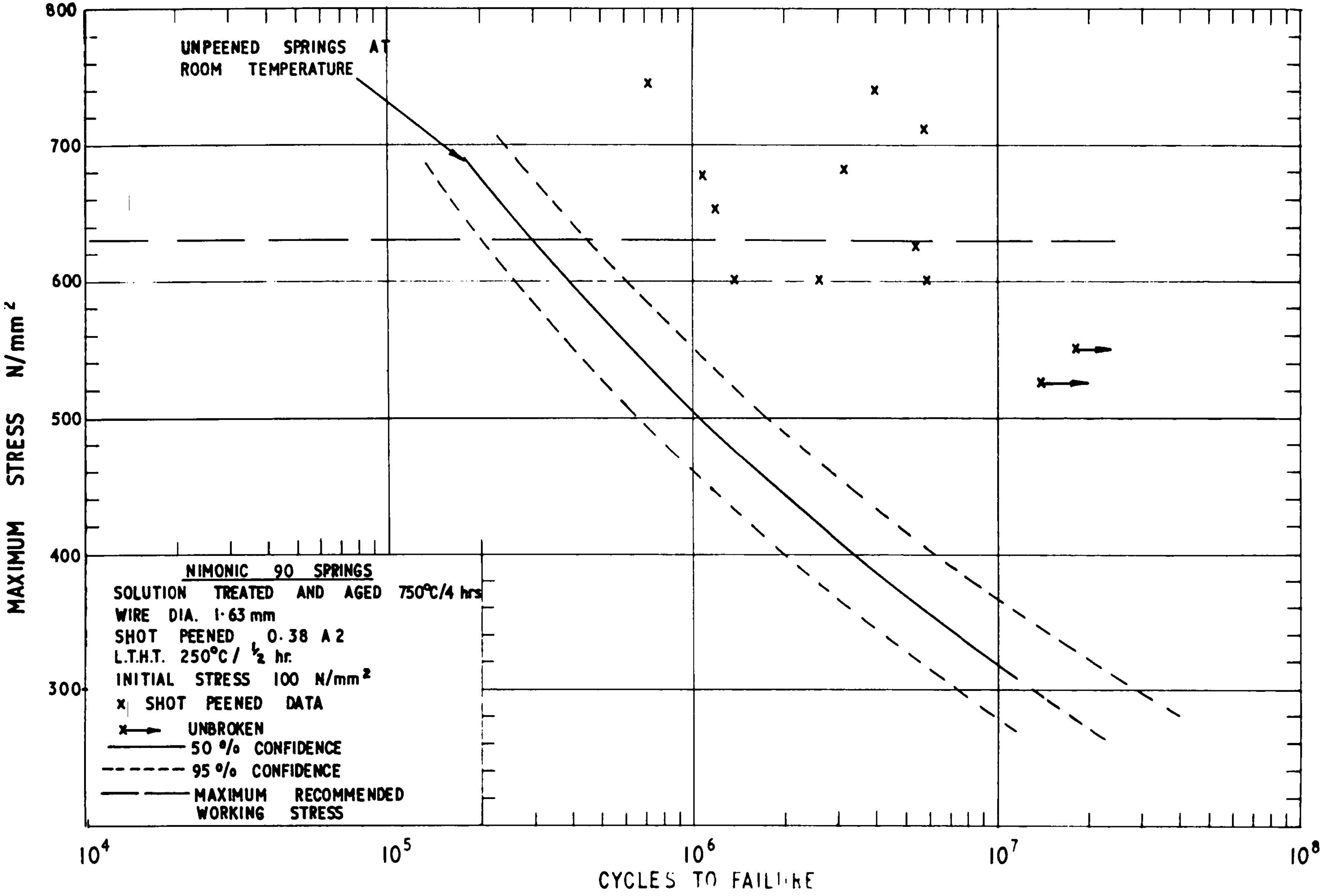

FIG. 6 S/N DATA FOR PEENED SPRINGS OF SOLUTION TREATED NIMONIC 90.

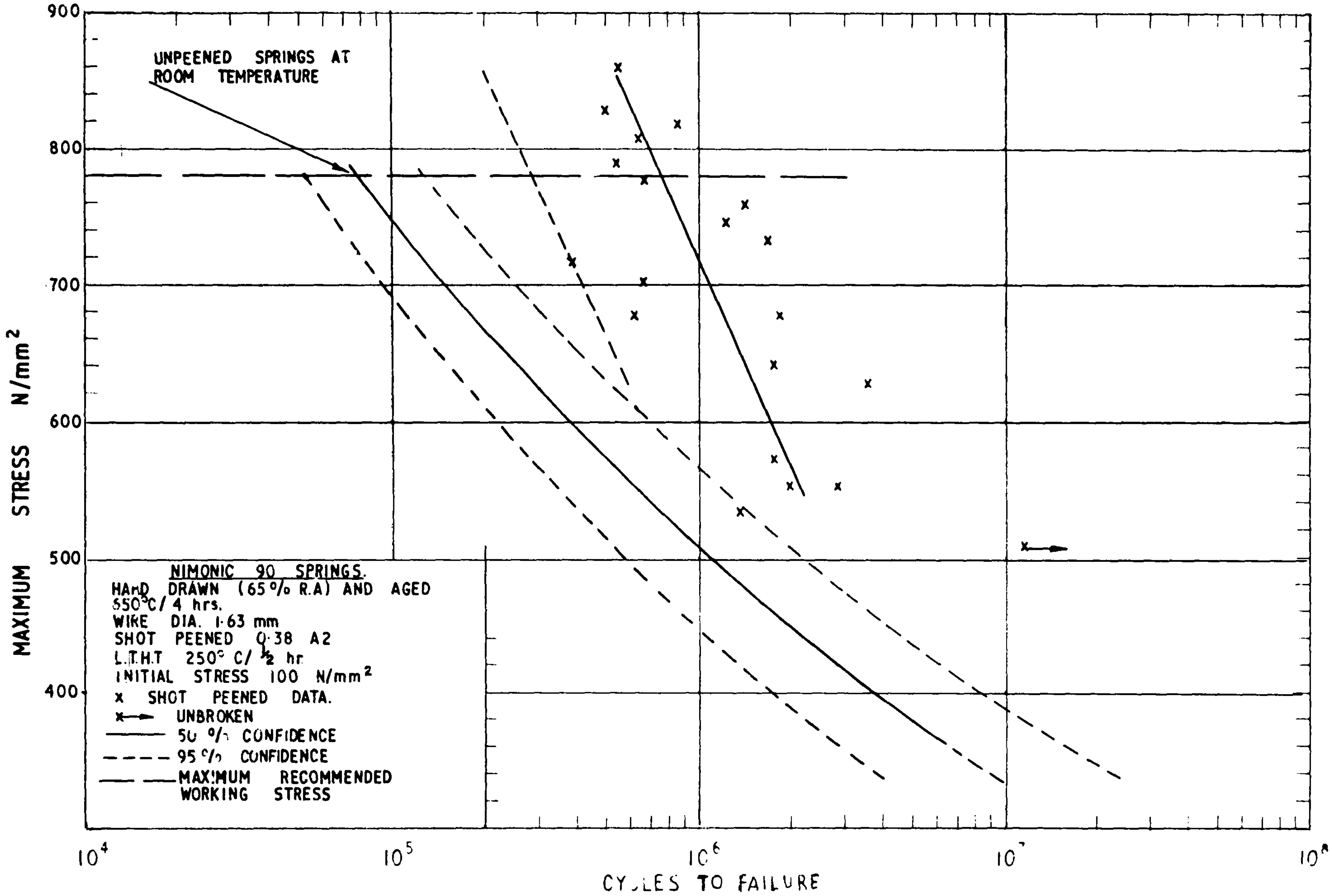

FIG. 7 S/N CURVE FOR PEENED SPRINGS OF HARD DRAWN NIMONIC 90

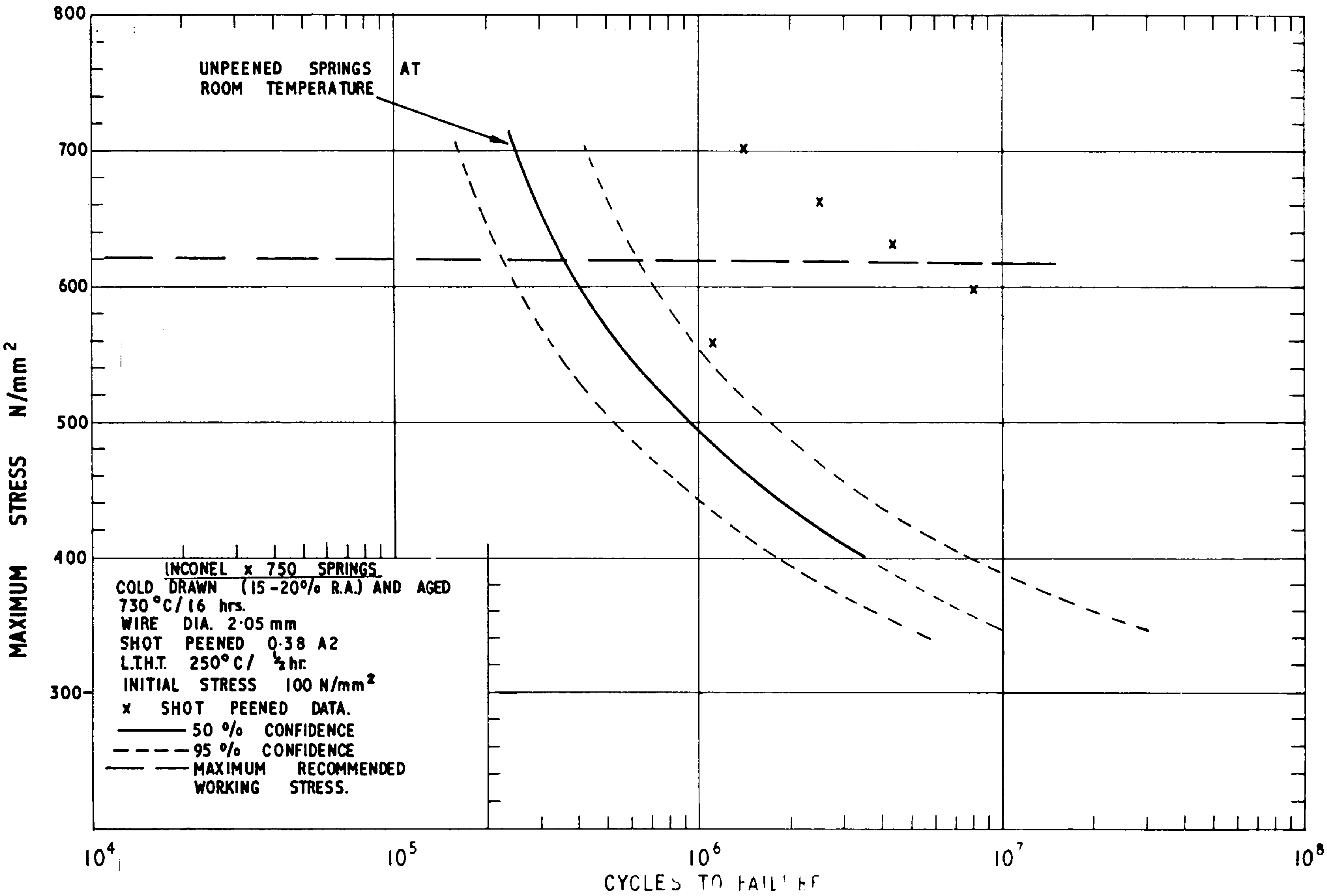

FIG. 8 S/N DATA FOR PEENED SPRINGS OF COLD DRAWN INCONEL x 750.

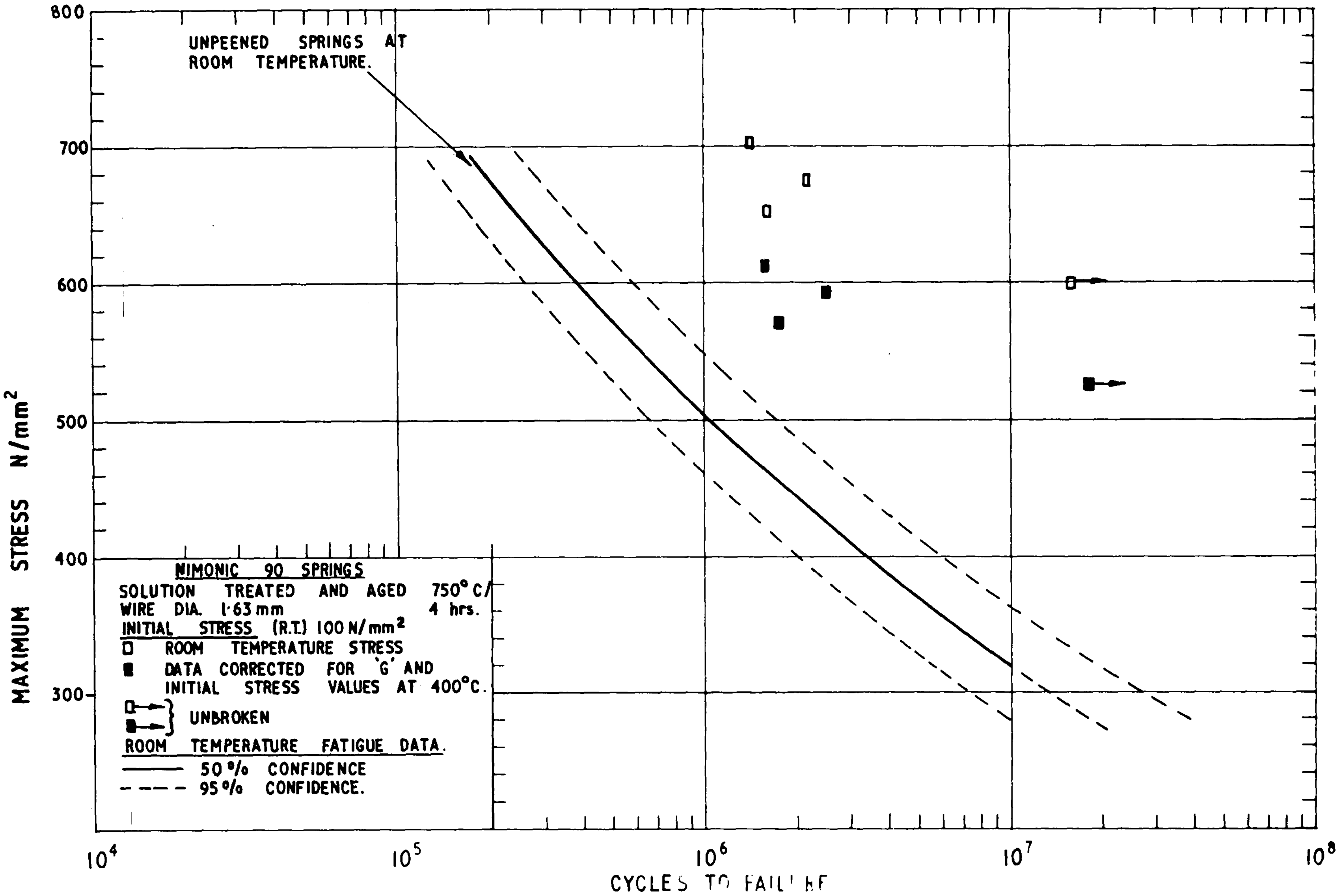

FIG. 9 S/N DATA FOR UNPEENED SPRINGS OF SOLUTION TREATED NIMONIC 90 AT 400°C.

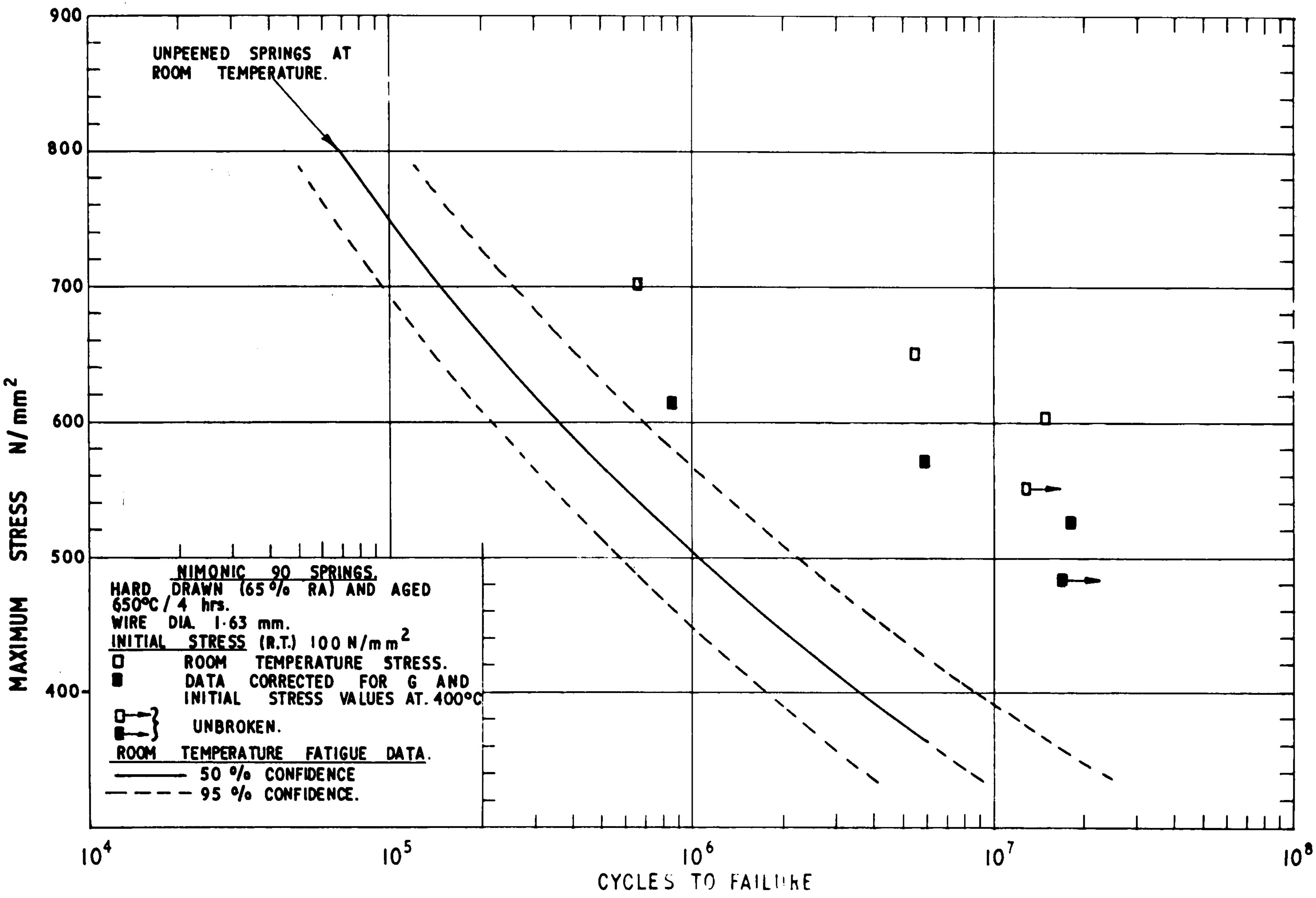

FIG. 10 S/N DATA FOR UNPEENED SPRING OF HARD DRAWN NIMONIC 90 AT 400°C.

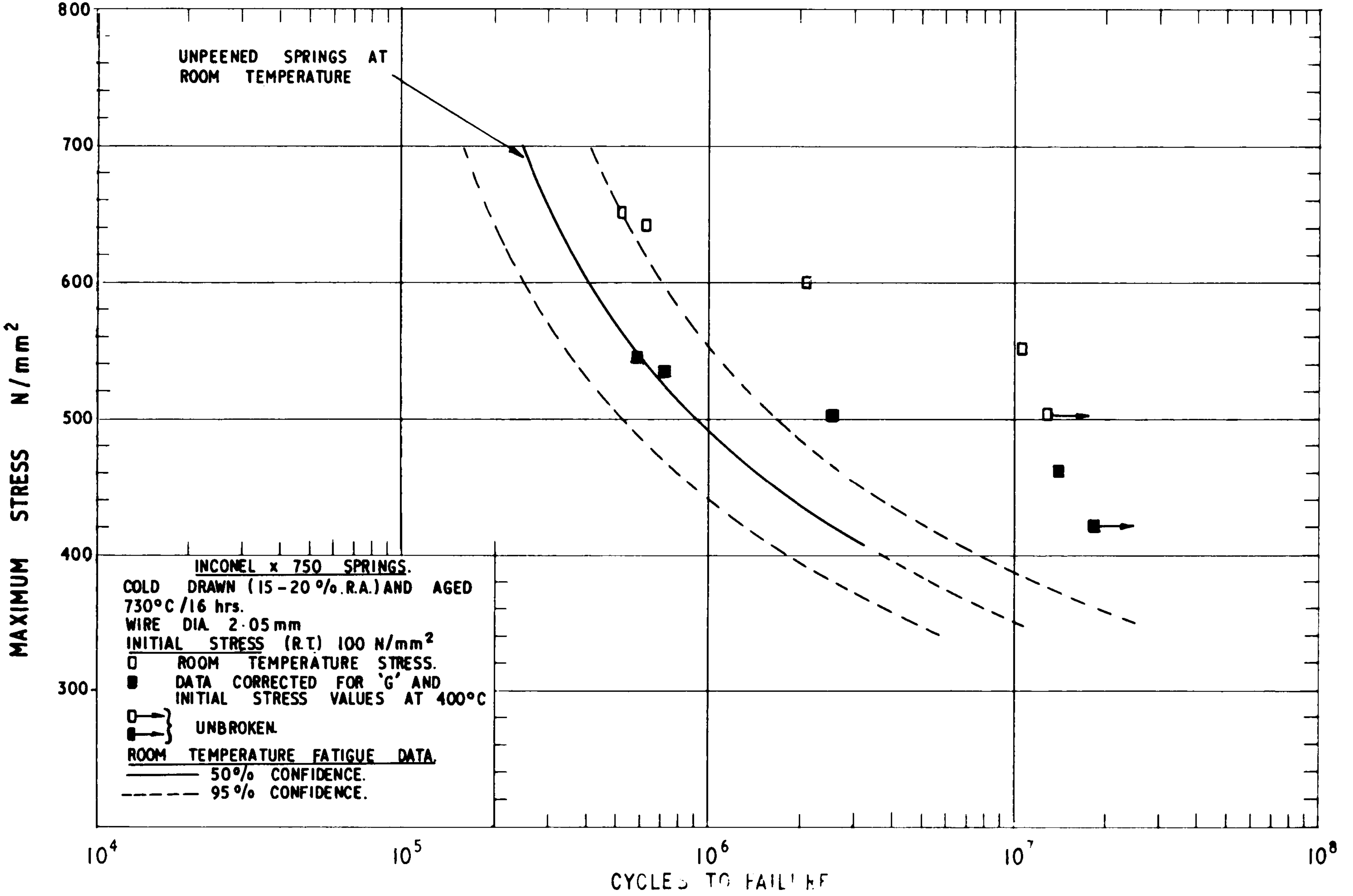

FIG. 11. S/N DATA FOR UNPEENED SPRINGS OF COLD DRAWN INCONEL x 750 AT 400°C.

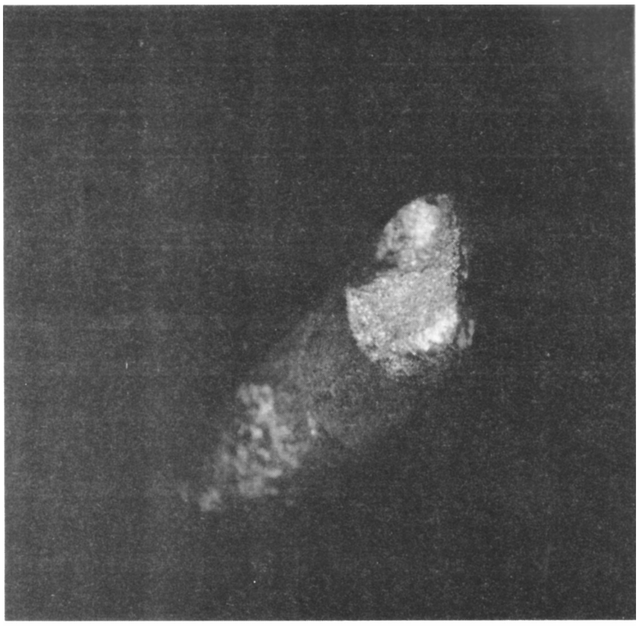

Fig. 12. X 10

Fracture surface of unpeened Nimonic 90 spring

Condition:

Solution treated and aged 750°C/4 hrs

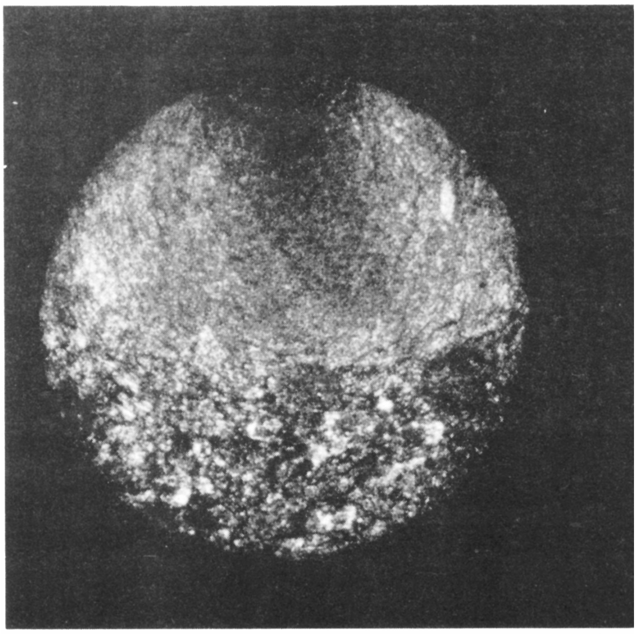

Fig. 13. X 42

Fracture surface of unpeened Nimonic spring

Condition:

Hard drawn and aged 650°C/4 hrs

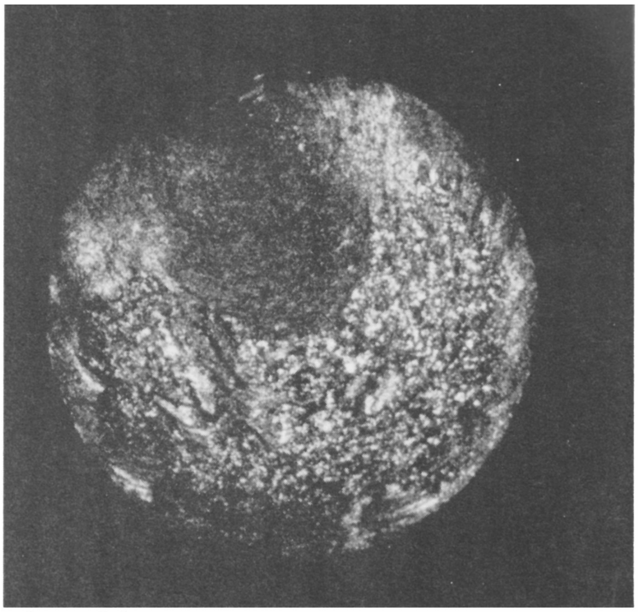

Fig. 14. X 42

Fracture surface of shot peened Nimonic 90 spring

Condition:

Hard drawn and aged 650°C/4 hrs shot peened 0.38/A2; L.T.H.T. 250°C/½ hr

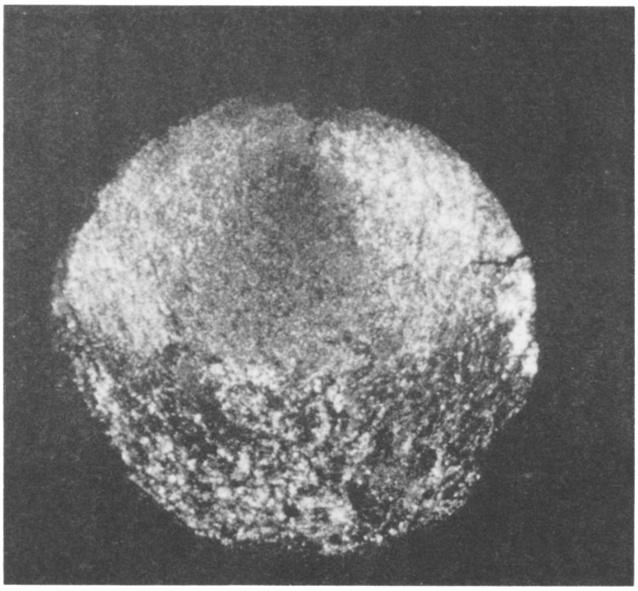

Fig. 15. X 42

Fracture surface of unpeened Nimonic 90 spring tested at 400°C

Condition:

Hard drawn and aged 650°C/4 hrs