THE SPRING RESEARCH AND MANUFACTURERS' ASSOCIATION

THE FATIGUE AND RELAXATION PROPERTIES OF MARAGING STEEL SPRINGS

by

K. Brummitt, B.Sc.

Report No. 279

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SUMMARY AND CONCLUSIONS

The high tensile strength, combined with good ductility and fracture toughness, of the maraging steels suggests that they might form a useful class of spring materials. However, very little information is available concerning the properties of these materials in wire or strip form. To determine the potential of maraging steels for spring applications, two types of maraging steel were obtained. A 18% Ni-Co-Mo steel in wire form and a stainless maraging steel in the form of 0.5 mm sheet were used for the investigation. The most suitable thermal treatments for the materials in the cold worked condition were determined. The fatigue and relaxation behaviour of springs coiled from the maraging steel wire were determined in both the shot peened and unpeened conditions. The fatigue and relaxation behaviour of the stainless maraging strip was also studied.

It was concluded that:

1. The most suitable ageing treatment for wire drawn from 18% Ni-Co-Mo steel was three hours at 480°C.

2. Unpeened springs manufactured from maraging steel wire had a poor fatigue strength.

3. Shot peening gave a large increase in fatigue strength, the shot peened springs had a superior fatigue performance to shot peened 17-7PH wire springs.

4. The maximum service temperature for 18% Ni-Co-Mo steels appears to be 350°C.

5. The most suitable ageing treatment for cold rolled stainless maraging strip was three hours at 500°C.

6. The fatigue properties of the as-aged stainless maraging strip were poor compared to those of CS80 and CS90 pre-hardened and tempered strip.

7. The maximum service temperature of the stainless maraging steel strip appears to be 350°C.

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THE FATIGUE AND RELAXATION PROPERTIES OF MARAGING ALLOY SPRINGS

by

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1. INTRODUCTION

If tensile strength were the only criterion for spring materials, then low alloy steels with tensile stengths in excess of 2800 N/mm^2 and hardness values in excess of 800 HV would be available. The carbon level required to achieve these values, however, seriously impairs other important properties such as ductility and toughness. The maraging steels are a relatively new class of steels developed to give higher strength levels together with good ductility and fracture toughness. This is achieved by producing a high nickel steel with a very low carbon content. On cooling from the austenite phase these steels for a body centered, cubic nickel martensite which is sufficiently ductile to be cold-worked. This martensite may then be age hardened to produce a high strength material. The precise nature of the ageing mechanism is not fully understood but it may be attributed to precipitation of intermetallic compounds on dislocations within the martensitic matrix some evidence for an ordering of the structure with ageing has also been found.

The first maraging steels belonged to the 18% nickel-cobalt-molybdenum, 20% nickel-titanium-aluminium or 25% nickel-titanium-aluminium groups. In an attempt to improve the corrosion resistance of these maraging steels, while still maintaining high strength and toughness levels, the stainless maraging steels were developed. In its simplest form the stainless material is a nickel-cobalt-molybdenum steel, with the nickel content reduced to 4-5% and to which 11-13% chromium is added. Such a material is currently being used in large quantities in one particular strip application.

A steel having high strength combined with good formability (in the solution treated condition) has some of the necessary features for a potential spring material.

In this report two types of maraging steel have been examined: an 18% Ni-Co-Mo maraging steel in the form of 2.65 mm dia. wire; and a stainless maraging steel in the form of 0.5 mm sheet.

2. MATERIALS

2.1 Maraging Steel Wire

At the present time no British supplier is producing maraging steel wire on a commercial scale, though some grades may be available from continental sources. It was necessary therefore to purchase a billet of maraging steel and have this processed into wire form.

A 64 kg billet of 18% Ni-Co-Mo steel to the Firth Brown G125 specification (similar to BSC Nimar 125) was purchased, and processed by rod rolling and cold drawing to 2.65 mm dia. wire. A 83% reduction in area was made following the final solution treatment to take advantage of any work hardening developed by the drawing operation. The chemical composition of the wire is given in Table I.

2.2 Stainless Maraging Steel Strip

The stainless maraging steel strip used in this investigation was produced by the British Steel Corporation under the name Kromar D70. The material was obtained as 220 mm wide cold rolled strip, having a thickness of 0.5 mm. The actual and specified chemical compositions are given in Table I.

3. SPRING DESIGN

Following preliminary tests to determine the optimum heat treatment, springs were coiled from the drawn G125 wire to the design given in Table II. After coiling, the springs were aged for three hours at 480°C to develop the optimum tensile strength. Approximately half the springs were shot peened to an Almen arc rise of 0.35-0.38 mm A2 using S230 shot. After shot peening the peened springs were given a further heat treatment for 30 minutes at 225^{o}C. These springs were used for both fatigue and stress relaxation measurements.

TABLE II SPRING DESIGN

Wire Diameter	2.65
Mean Diameter	21.2
Active Coils	3.5
Total Coils	5.5
Spring Index	8
Free Length (after grinding and prestressing)	48.1
Solid Stress	1620

4. STRIP PREPARATION

Following initial testing to determine the optimum heat treatment for the as-received material, approximately one hundred rectangular fatigue specimens, measuring 17.5 x 60.3 mm, were produced by cutting pieces from the as-rolled strip and, using a jig, a number of specimens were milled to size simultaneously. The edges were polished logitudinally with abrasive paper to remove machining marks and also to round off sharp corners. All of the fatigue specimens were manufactured so that their longitudinal axes were parallel to the rolling direction. The specimens were then aged for three hours at 500^{o}C prior to testing.

Specimens for stress relaxation testing were carefully cut to size using a metallographic 'cut-off' machine, thereby minimising the introduction of residual stress to the strips by the cutting action. The specimens, which were rectangular 20 x 65 mm strips, were then aged at 500^{o}C for three hours in order to develop their optimum strength. By clamping the strips flat in a jig during the ageing process, it was possible to affect a thermal flattening operation which greatly assisted the subsequent relaxation tests.

5. EXPERIMENTAL PROCEDURE

5.1 Ageing Trials

Maraging steels are normally obtained in the solution treated condition and aged after machining to develop optimum properties in the material. The materials used in this investigation were in the cold worked condition. It was therefore necessary to establish whether the recommended ageing treatments were suitable for material in this condition and in particular, if a further solution treatment was necessary before ageing. In the case of the G125 material it was also necessary to check the ageing temperature because of the danger of reversion to austenite if too high an ageing temperature is used. The various heat treatments and results obtained are shown in Tables III and IV.

In neither case was it necessary to re-solution treat the material. An ageing temperature of 480°C for three hours was found to be the optimum ageing treatment for the G125 maraging wire. The recommended[1] ageing treatment of 500°C for three hours was found satisfactory for the stainless maraging steel strip.

TABLE III PROPERTIES OF 18% Ni-Co-Mo WIRE AFTER VARIOUS HEAT TREATMENTS

Condition	R_m N/mm^2	$R_{p0.1}$ N/mm^2	Hardness HV30
As-drawn	1390	1150	375
Aged 460°C 3 h	2280	2240	-
Aged 480°C 3 h	2300	2290	663
Aged 500°C	2290	2240	-
Solution treated and aged 480°C 3 h	2070	1940	618

TABLE IV PROPERTIES OF STAINLESS MARAGING STEEL STRIP AFTER VARIOUS HEAT TREATMENTS

Condition	R_m N/mm²	$R_{p.01}$ N/mm²	Elongation %	Hardness HV30
As rolled	1240	1050	3.0	404
Air cooled from 870°C and aged at 500°C	1660	1580	3.1	571
Water quenched from 870°C and aged at 500°C	1760	1690	3.0	553
As rolled and aged at 500°C	1830	1790	1.0	586

5.2 Fatigue Testing of Springs

The springs were individually load tested to determine the deflection necessary to achieve the necessary stress range and fatigue tested using a multiple stage, forced motion fatigue testing machine. The springs were tested to a maximum of 10^7 cycles to enable S/N curves to be drawn (Figs. 1 and 2). Modified Goodman diagrams for both unpeened and shot peened springs were drawn from these curves and are shown as Figs. 3 and 4.

5.3 Fatigue Testing of Stainless Maraging Strip

Fatigue testing of the strip samples was carried out on a forced motion fatigue testing machine operating at 25 Hz. The technique for load testing thin strip specimens for fatigue testing on this machine has been described previously[2]; this procedure was adhered to throughout this investigation. Specimens were tested from initial stresses of 100, 300 and 500 N/mm² to a maximum stress which varied from 800 to 1670 N/mm². Three S/N curves were established and are presented in Fig. 5. A modified Goodman diagram for lives of 10^5 and 10^6 cycles was drawn from these curves and is shown in Fig. 6.

5.4 Stress Relaxation of Maraging Steel Wire Springs

Springs were individually load tested to determine the compressed length which gave the desired test stress. The springs were then compressed to the pre-determined length using stainless steel nut and bolt assemblies. After heating at the selected test temperature for the required period of time, the springs were allowed to air cool to room temperature before being dismantled from the bolts. Each spring was then load tested to the test length and the new load noted, from which the relaxation as a percentage of the original load was calculated.

The relaxation with time at 300°C for two stress levels was determined over a 200-hour period. As almost all the relaxation took place within the first 100 hours (Figs 7 and 8), the remaining work was confined to a 120-hour period.

The relaxation behaviour of springs at five stress levels at temperatures of 300, 350 and 400°C for both shot peened and unpeened springs was determined and the results are shown in Figs. 9, 10 and 11.

5.5 Stress Relaxation of Stainless Maraging Steel Strip

Initially attempts were made to measure the stress relaxation of strip using a three point bending jig of the type described by Gohn et al[3] (Fig. 12) but experience soon showed that this type of jig was unsuitable. The type of jig finally used for the tests is shown in Fig. 13. The strips were clamped over a cylindrical former, the radius of which had been designed to give the appropriate stress. The jigs were then placed in a furnace at the test temperature for 120 hours, after which the jigs were air cooled to room temperature before the strips were removed.

Using a workshop profile projector the plastic deformation in terms of the arc rise of the strip over a 60 mm gauge length was measured and from this, the radius of curvature was calculated. It can be shown that the reciprocal of the ratio of the radii of curvature of the strip in the jig and after testing is equal to the relaxation.

$$R = \frac{A_1}{A_o} \times 100$$

A_1 = arc rise after testing

A_o = arc rise when in jig

R = percentage relaxation

This method of testing has the advantage that the same stress is applied along the entire length of the strip, as compared to the three point bending method, where the stress varies continuously along the strip. The results of this testing are given in Table V.

6. DISCUSSION

6.1 Fatigue Properties

The fatigue properties of springs manufactured from the 18% Ni-Co-Mo maraging steel wire can be seen in Figs. 1 to 4. Although the data obtained from unpeened springs show a close relationship between the maximum stress and fatigue life (Fig. 1), there is such a degree of scatter in the results for shot peened springs (Fig. 2) that no relationship between maximum stress and fatigue life can be found. The S/N curves have therefore been drawn below all the broken specimens. It was noticed that some of the shot peened springs had failed under the end coils and other springs had failed in the central coils. It was thought that the position of the failure might be related to fatigue life and the presence of two separate modes of failure might explain the scatter. Examination of the data failed to show any evidence of such a relationship. The scatter in results may have occurred because the shot peened springs were tested only at maximum stresses near the 10^7 cycles fatigue strength, where the distribution of fatigue failures is much wider than at stresses well above the fatigue limit. Unfortunately, it was not possible to test springs to higher maximum stresses due to limitations on the stroke of the testing machines used. To confirm that the scatter is due to testing near the 10^7 fatigue strength, it would be necessary to undertake further testing using springs with a higher stress level for the same deflection in order to achieve higher stresses. There appears to be a sharp division between springs which fail and those which survive to 10^7 cycles but, as there are insufficient data for a statistical determination to be made of the fatigue strength at 10^7 cycles, this could be a chance occurrence. It should be noted that these maraging steels may not exhibit a true fatigue limit but may behave in the manner of non-ferrous metals. The limits drawn are estimates of the fatigue strength at 10^7 cycles and not fatigue limits.

In the unpeened condition, the fatigue performance of the springs was disappointingly low for a material with such a high tensile strength. The 10^7 cycles fatigue ratio was 0.20 and the fatigue strength for 10^7 cycles at zero initial stress was only 450 N/mm^2. These figures compare unfavourably with conventional patented carbon steel spring wire.

Shot peening had a dramatic effect on the fatigue properties of the springs, increasing the fatigue strength at 10^7 by 130%. This increase is large compared to that normally found with springs manufactured from carbon steel wires, but very large improvements in fatigue performance have previously been encountered with springs manufactured from stainless steel(4,5). Very great improvements in the fatigue strength of maraging steels as a result of shot peening or other working after ageing have also been reported for specimens in tensile fatigue(6).

It was noted that the springs had a poor surface finish after ageing, which would normally be expected to lead to an inferior fatigue performance. The great improvement brought about by shot peening may be largely due to the removal of the poor surface left after the ageing treatment.

The fatigue results obtained from the stainless steel maraging strip are shown in the form of S/N curves (Fig. 6) from which the modified Goodman diagram Fig. 7 was drawn.

The fatigue strength of this material, like that of the unpeened 18% Ni-Co-Mo wire, is poor for a material with such a high tensile strength. The fatigue strength at an endurance of 10^6 cycles was only 840 N/mm^2 at zero initial stress, even though the tensile strength was as high as 1830 N/mm^2. This result compares unfavourably with pre-hardened and tempered high carbon steel strip tested in previous work(7). For CS80 with a tensile strength of 1655 N/mm^2, the fatigue limit at zero initial stress was 960 N/mm^2 and, for CS90 strip with a tensile strength of 1780 N/mm^2, the fatigue limit at zero initial stress was 1180 N/mm^2.

It is clear therefore that in the as-aged state that maraging steels exhibit inferior fatigue properties to those of cheaper spring materials already in use.

The extremely high fatigue strength of springs manufactured from maraging wire and peened after ageing was more promising. At zero initial stress, the 10^7 endurance limit is 270 N/mm^2 higher than that for shot peened springs manufactured from 17-7PH wire(8). This suggests that a much better fatigue performace might be obtained from maraging strip if samples were shot peened or some additional rolling were carried out after the ageing treatment. If improvements in fatigue performance can not be achieved, it is unlikely that stainless steel maraging strip has a future as a dynamic spring material.

6.2 Relaxation Behaviour

The relaxation of the 18% Ni-Co-Mo wire springs with time was measured, in both the shot peened and unpeened conditions, at two stress levels for up to 200 hours at 300°C (Figs. 8 and 9). The results indicated that the rate of relaxation occurring after 100 hours was very small and further testing was therefore restricted to 120 hours. Comparison of the data in Figs. 7 and 8 shows a large increase in relaxation as a result of shot peening but there was no significant difference in the curves obtained for 600 and 1000 N/mm^2 in either the unpeened or shot peened conditions. The results of testing at both stress levels were therefore compbined and a single line drawn to represent the data in each case (Figs. 7 and 8).

This insensitivity of the relaxation behaviour to stress is reflected in the very flat stress relaxation curves obtained at 300°C (Fig. 9). At higher temperatures a greater dependence on stress is observed. The shot peened springs show quite a strong stress dependence at 350°C but with the unpeened springs a dependence on stress is only significant at 400°C for a 120-hour period. If 10% is regarded as the maximum allowable relaxation, then the maximum service temperature for this material would be in the region of 350°C. At 400°C the relaxation of approximately 16-18% may be too great for most service applications. Shot peening, which proved extremely beneficial to the fatigue properties of the springs, had the usual detrimental effect on the relaxation properties of the springs.

Because of experimental difficulties, very few accurate data have been obtained for the stress relaxation behaviour of stainless steel maraging strip. The data which are available are shown in Table V. The limited amount of data available indicate a maximum service temperature of approximately 400°C for stresses up to 1450 N/mm^2. This is superior to that for pre-hardened and tempered carbon steel strip[9]. Unfortunately, there is very little published information on the stress relaxation behaviour of other materials in strip form.

TABLE V RELAXATION PROPERTIES OF MARAGING STRIP

Stress N/mm^2	Temperature °C	Mean Relaxation %
1090	320	8.2
1090	370	7.8
1090	420	10.4
1450	320	7.0
1450	370	10.1
1450	420	10.6

To what extent the results of these tests are representative of the long term stress relaxation behaviour of the maraging steels is open to some doubt, as the effect of prolonged high service temperatures on maraging steels can be complex.

The recommended ageing treatments which were used [1,10,11] do not develop the maximum hardness in the steel. The maraging steels do exhibit a flat ageing curve but long term exposure to elevated temperatures will cause further ageing of the material.

In the 18% Ni-Co-Mo steel, over-ageing may occur but in these materials it is not generally regarded a problem. Because of the high nickel content, the A_{c1} is low and reversion to austenite takes place at temperatures as low as 400°C with prolonged heating. Although it has been postulated that small amounts of austenite in the structure have a hardening effect[12], further reversion certainly causes a decrease in hardness similar to that which would be experienced from over-ageing. The temperature at which this reversion takes place determines the upper working temperature of the alloy. The large increase in relaxation of the 18% Ni-Co-Mo wire over the interval 350-400°C therefore agrees with the observation of reversion to austenite at 400°C[10,12]. Stainless maraging steel has a much lower nickel content and contains approximately 12 wt % chromium (a ferrite stabiliser): hence the A_{c1} of the stainless material is higher than that of the plain 18% Ni-Co-Mo alloy and reversion to austenite does not present a problem. Thus the material should be more suitable for high temperature use than the 18% Ni-Co-Mo alloy. In fact if the 10% relaxation criterion is used, then the maximum operating temperature of the stainless strips will only be 370/420°C. However, the results do not show that a large increase in relaxation occurs over the 370° - 420° interval, as took place in the 18% Ni-Co-Mo springs over the 350 - 400°C interval. This suggests that the relaxation of the stainless maraging steels at high temperatures may be superior, but it is not possible to quantify this, as the two materials were tested in different stress modes. The difference may not be of importance to the spring industry, since, at the temperatures at which this difference is found, the relaxation is too great for normal spring applications. If the maraging steels are to be developed for higher temperature spring applications, attention should be directed towards the stainless maraging steels or the 15% Ni-Co-Mo steels(12,13) developed for high temperature use.

6.3 Potential as a Spring Material

The combination of high strength, ductility and fracture toughness has already lead to the wide use of maraging steels in the aerospace field and in other applications where the advantages of maraging steels justify the cost of using double vacuum melted steel. The high strength, combined with good fatigue performance and elevated temperature resistance, of shot peened 18% Ni-Co-Mo wire springs suggests that spring applications may be found for maraging steels in this condition.

Good resistance to moderately high temperatures together with high strength levels suggests that uses may be found in static applications at moderately high temperatures when the stress conditions are too high to be met by other heat resisting materials such as En 58A, Nimonic 90 or Inconel X750.

The use of maraging steels in strip form is likely to be limited to static applications unless some form of working after ageing can produce an increase in fatigue properties similar to that produced by shot peening the 18% Ni-Co-Mo springs.

7. CONCLUSIONS

1. The most suitable ageing treatment for wire drawn from 18% Ni-Co-Mo steel was three hours at 480°C. No further solution treatment was necessary.

2. Unpeened springs manufactured from maraging steel wire had poor fatigue strength.

3. Shot peening gave a great increase in fatigue strength, the shot peened springs having a superior fatigue performance to 17-7PH wire springs.

4. The maximum service temperature for 18% Ni-Co-Mo steels appears to be about 350°C.

5. The most suitable ageing treatment for cold rolled stainless maraging strip was three hours at 500°C. No further solution treatment was found necessary.

6. The fatigue properties of the as-aged stainless maraging steel strip were poor compared to those of CS 80 and CS 90 pre-hardened and tempered strip.

7. The maximum service temperatures of the stainless maraging steel strip appears to be about 350°C.

RECOMMENDATIONS FOR FURTHER WORK

The high fatigue strength (after shot peening), combined with reasonable elevated temperature resistance, indicates that there is a potential for the use of maraging steel for springs, despite the high cost. To facilitate the use of these materials further work along several lines is needed.

a. For elevated temperture use, stainless maraging steel wire and the 15% Ni-Co-Mo quality[(13)] should be evaluated.

b. In the case of flat strip material for dynamic applications, work is needed to determine the effect of post-ageing mechanical treatments with a view to improving fatigue properties.

c. As the potential for maraging steel springs seems to lie in highly stressed dynamic applications, the determination of fatigue data with full statistical levels of confidence is necessary.

d. Because the effect of high temperatures on the structure of these materials can be complex, it would be desirable to perform a limited number of relaxation tests over long periods of time in order to be confident of the behaviour of maraging steels in high temperature service.

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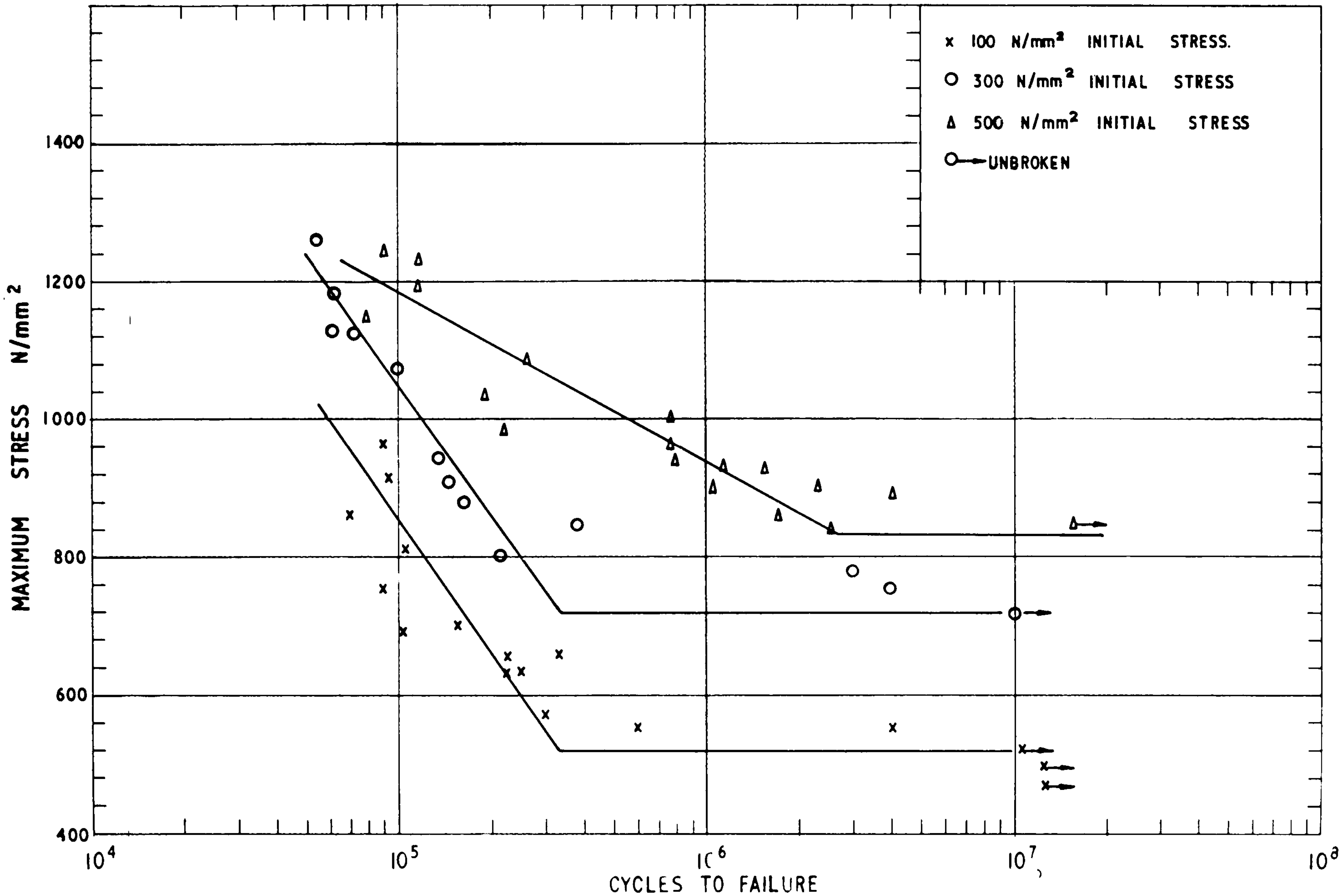

FIG. I S/N CURVES FOR UNPEENED SPRINGS MANUFACTURED FROM 18% Ni Co Mo WIRE.

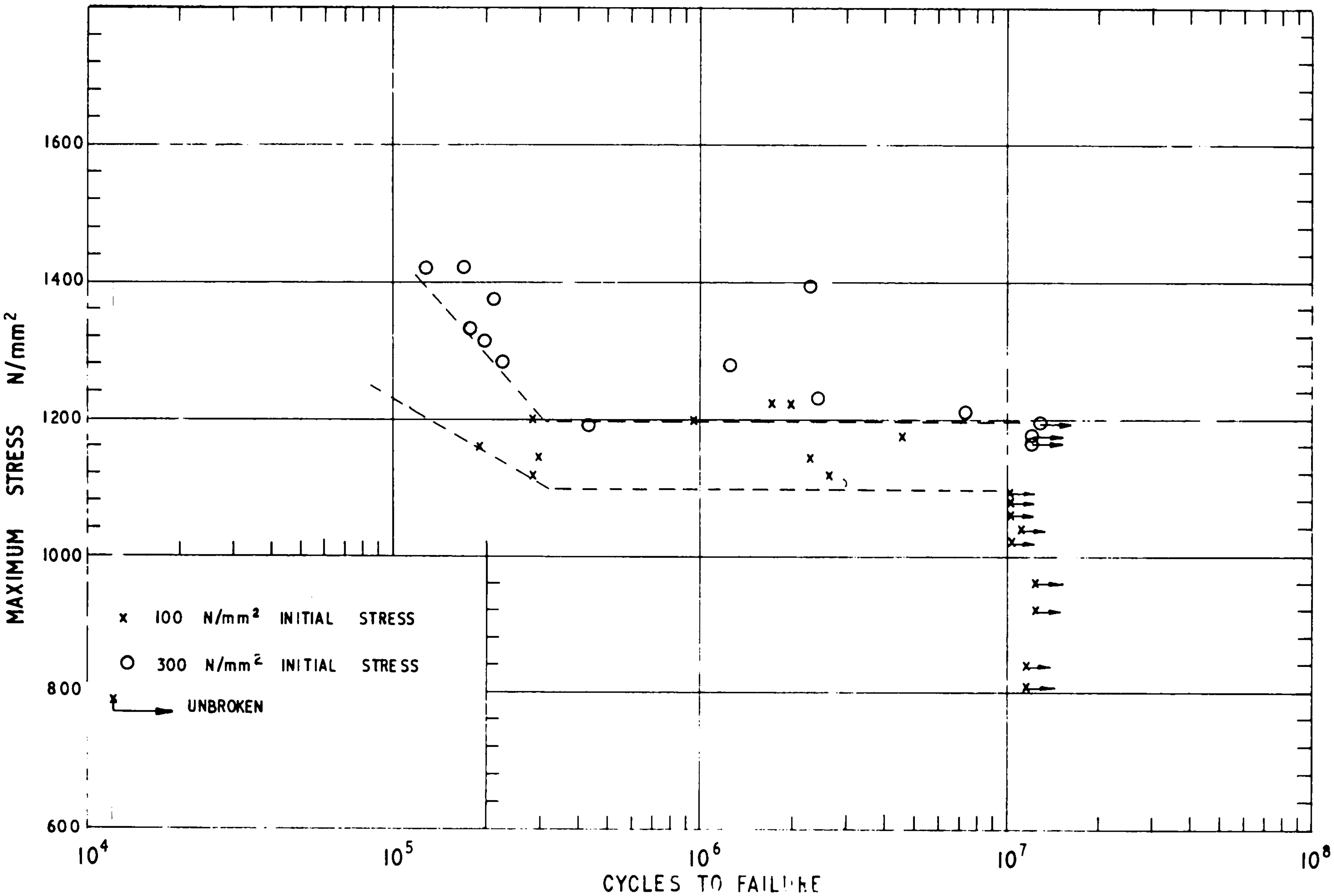

FIG. 2 S/N CURVES FOR SHOT PEENED SPRINGS MANUFACTURED FROM 18 % Ni Co Mo WIRE.

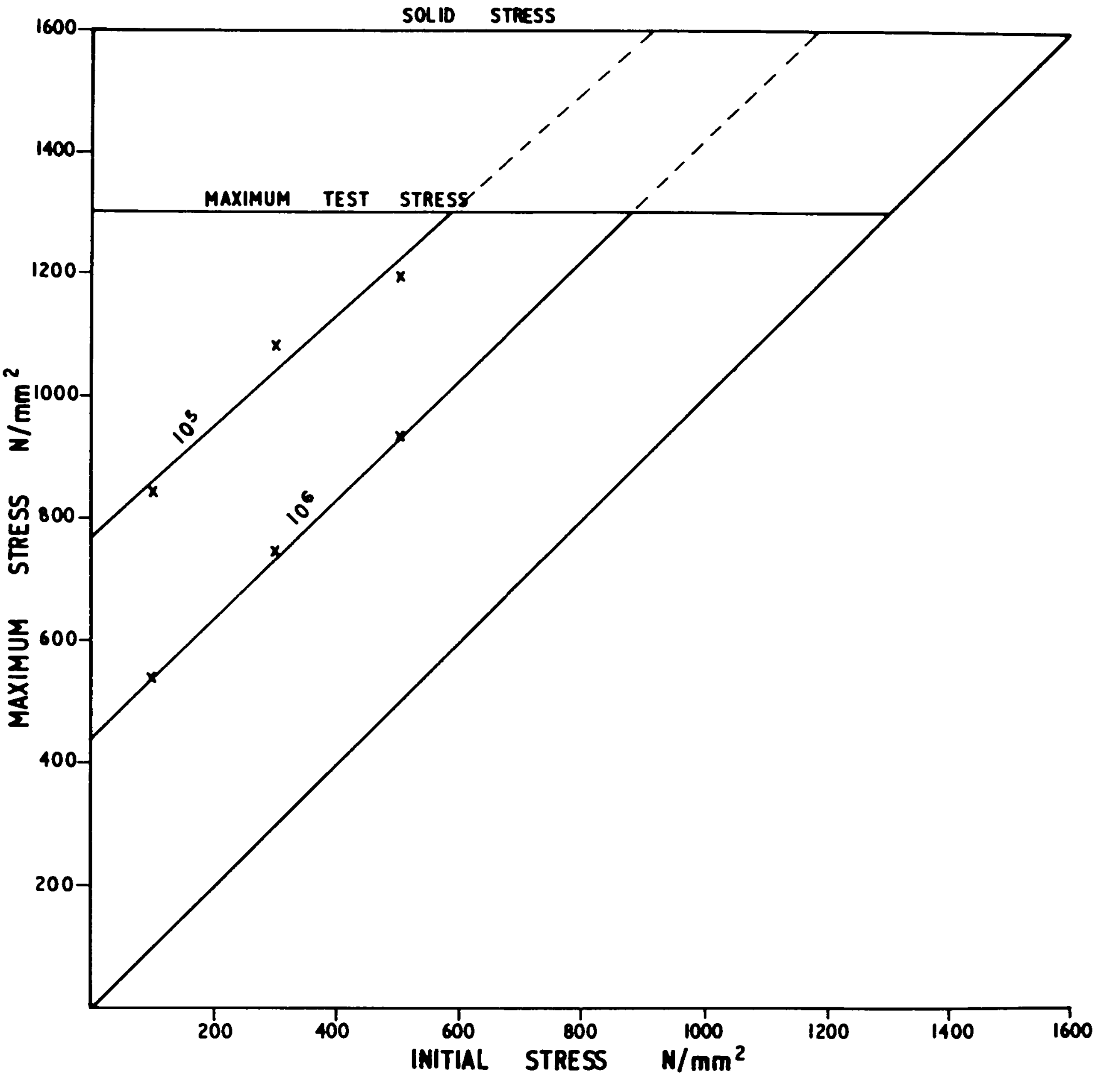

FIG. 3 MODIFIED GOODMAN DIAGRAM FOR UNPEENED SPRINGS MANUFACTURED FROM MARAGING STEEL WIRE. (MEAN DATA)

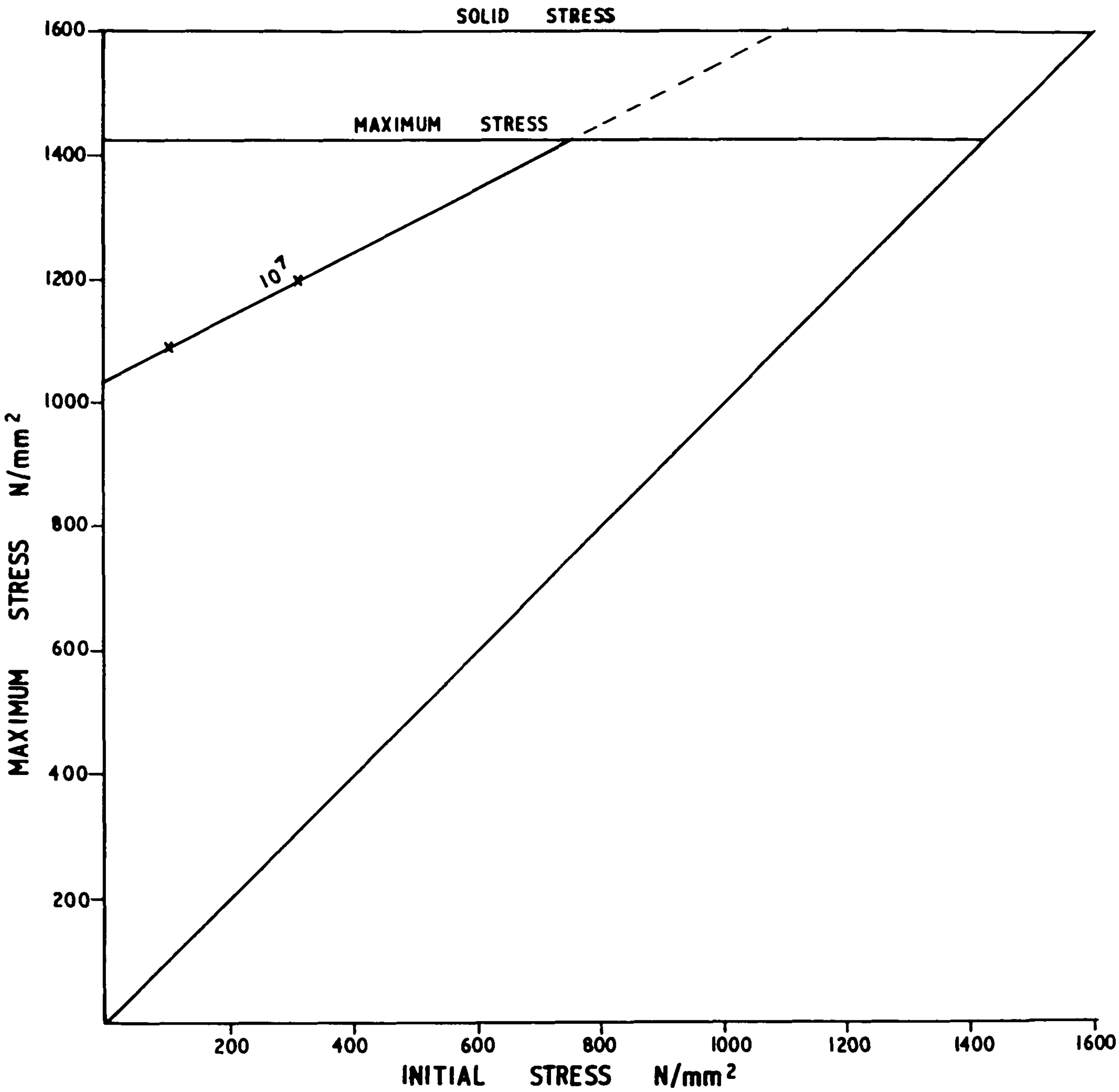

FIG. 4 MODIFIED GOODMAN DIAGRAM FOR SHOT PEENED SPRINGS MANUFACTURED FROM MARAGING STEEL WIRE (MEAN DATA.)

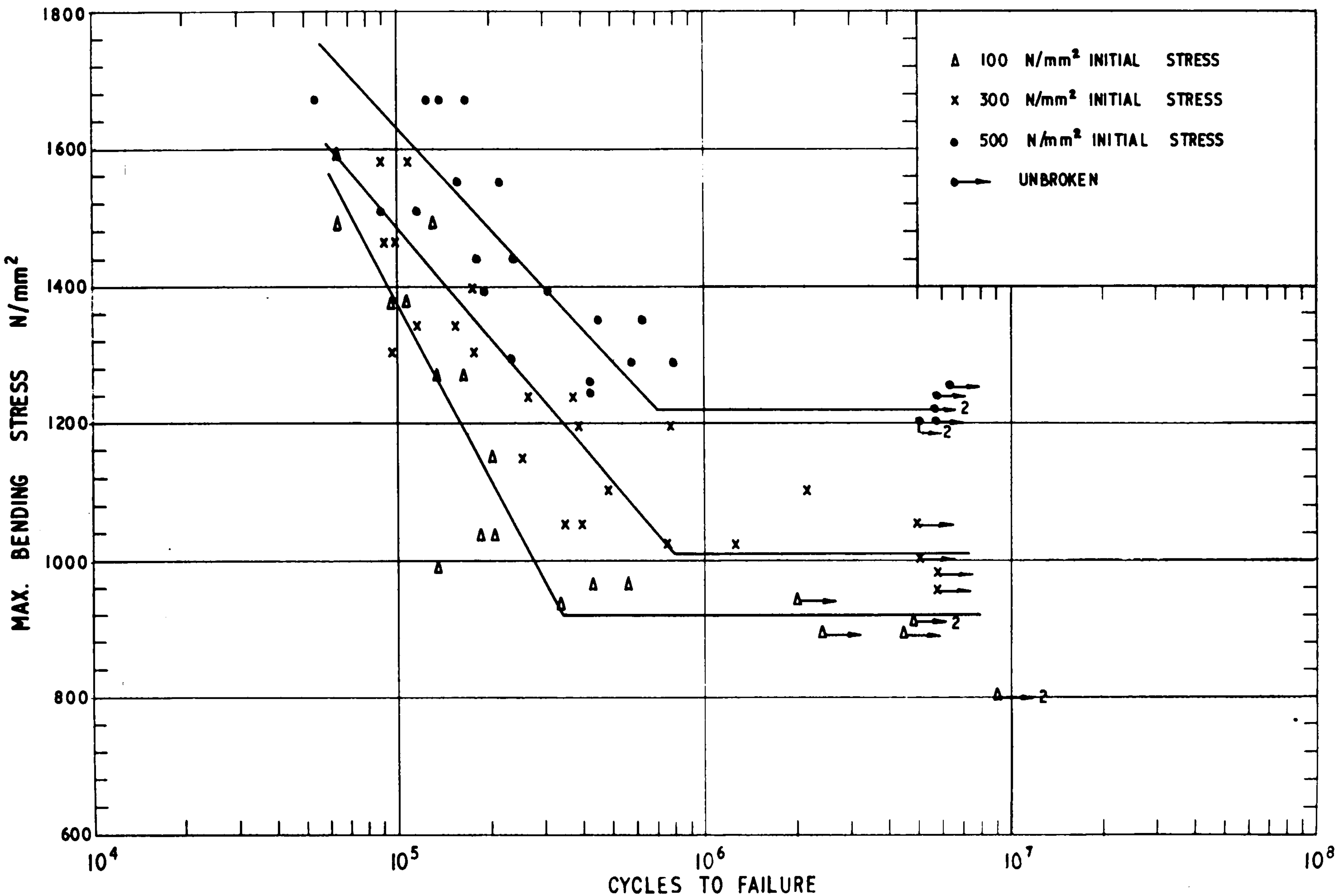

FIG. 5 S/N CURVES FOR STAINLESS MARAGING STRIP.

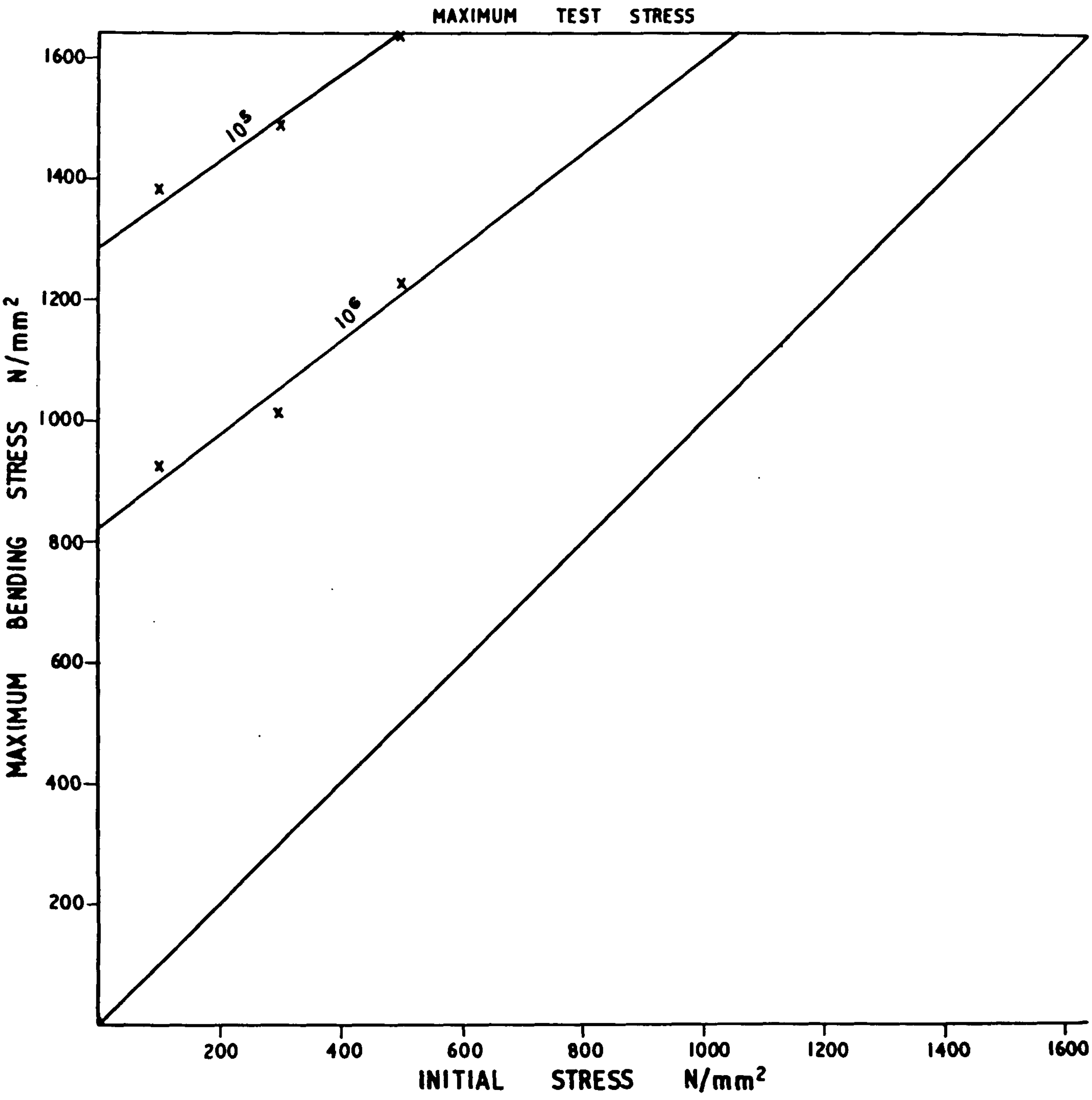

FIG. 6 MODIFIED GOODMAN DIAGRAM FOR STAINLESS MARAGING STRIP (MEAN DATA)

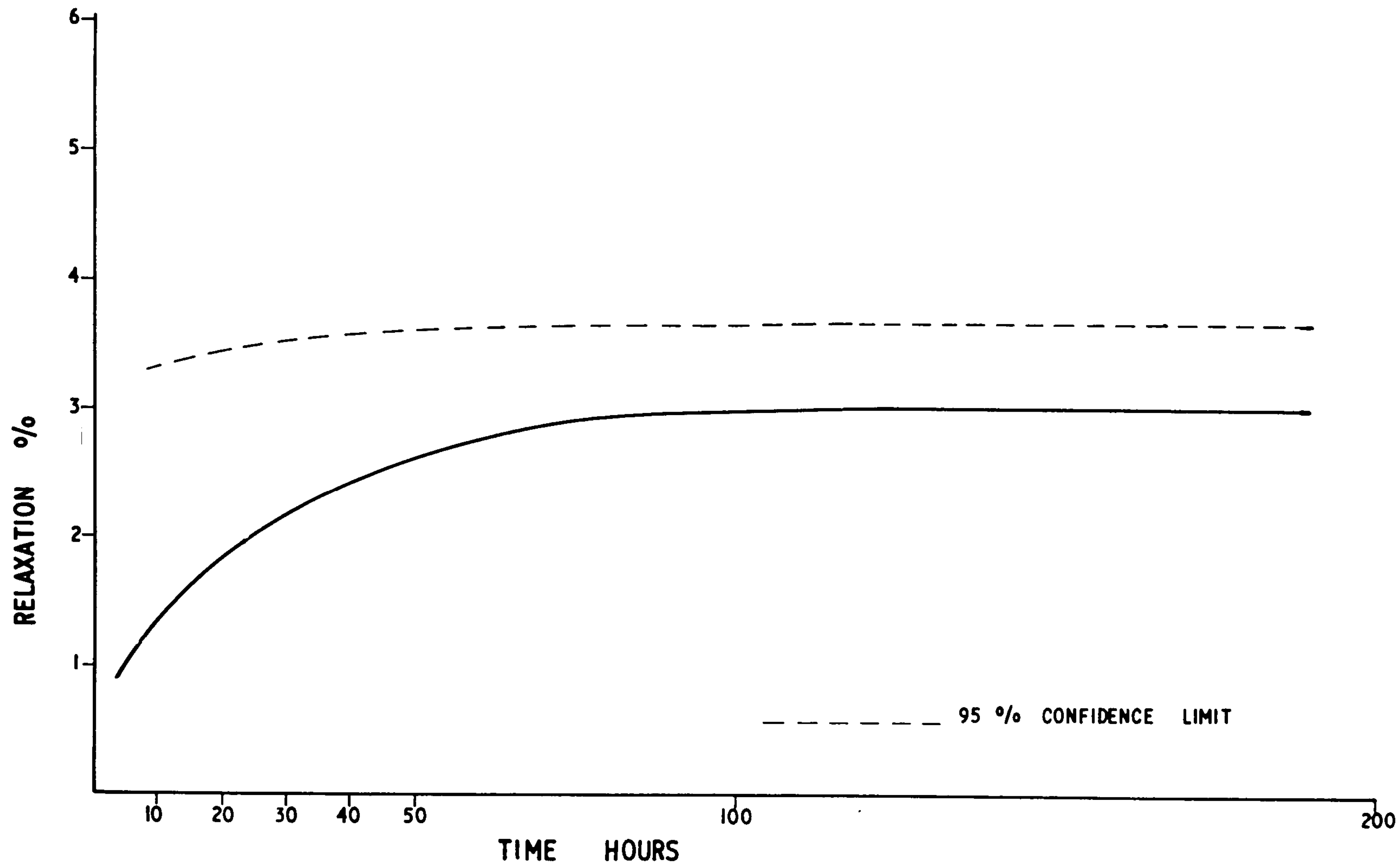

FIG. 7 RELAXATION OF UNPEENED 18 % Ni Co Mo MARAGING STEEL SPRINGS WITH TIME AT 300° C.

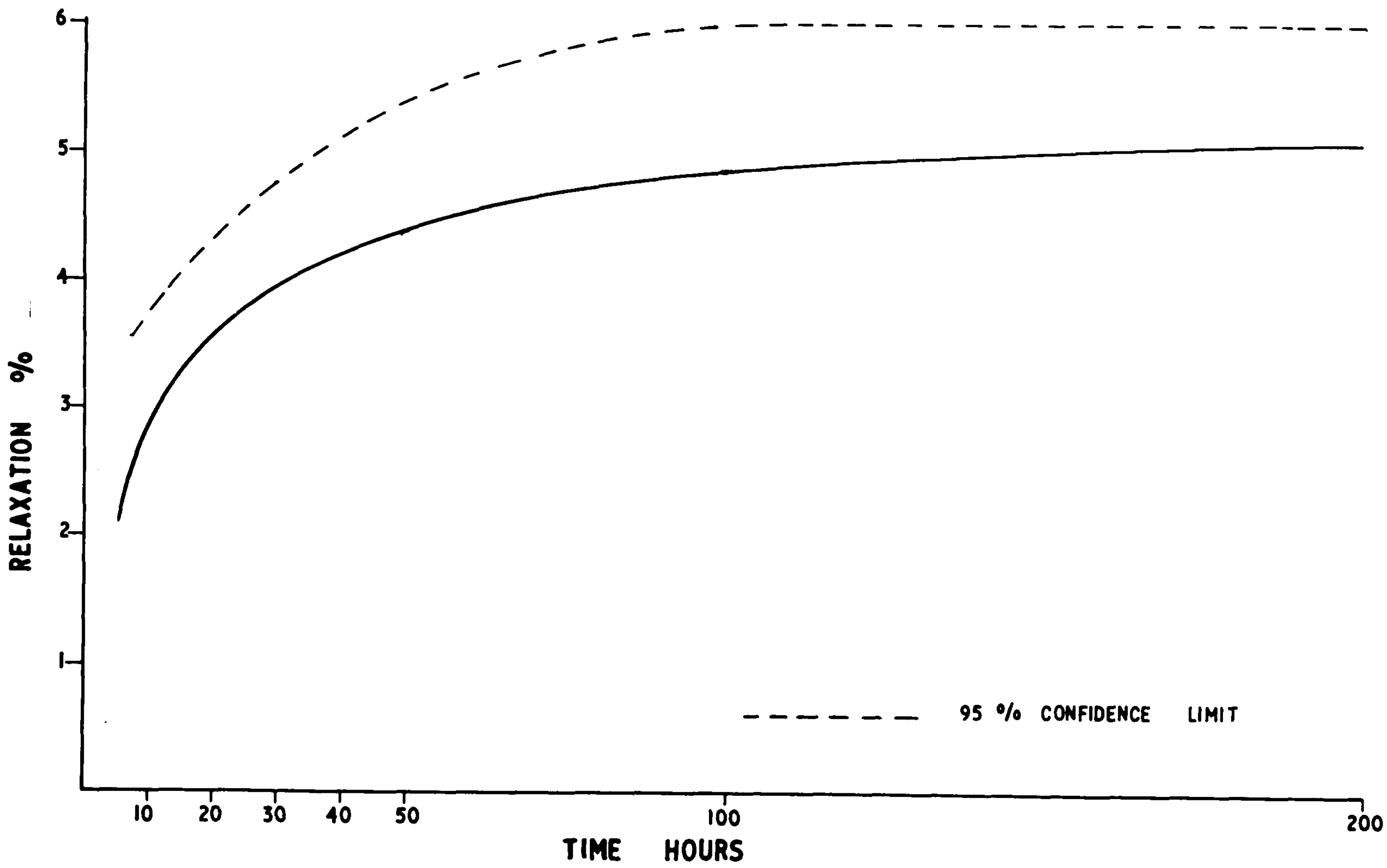

FIG. 8 RELAXATION OF SHOT PEENED 18% Ni Co Mo MARAGING STEEL SPRINGS WITH TIME AT 300° C

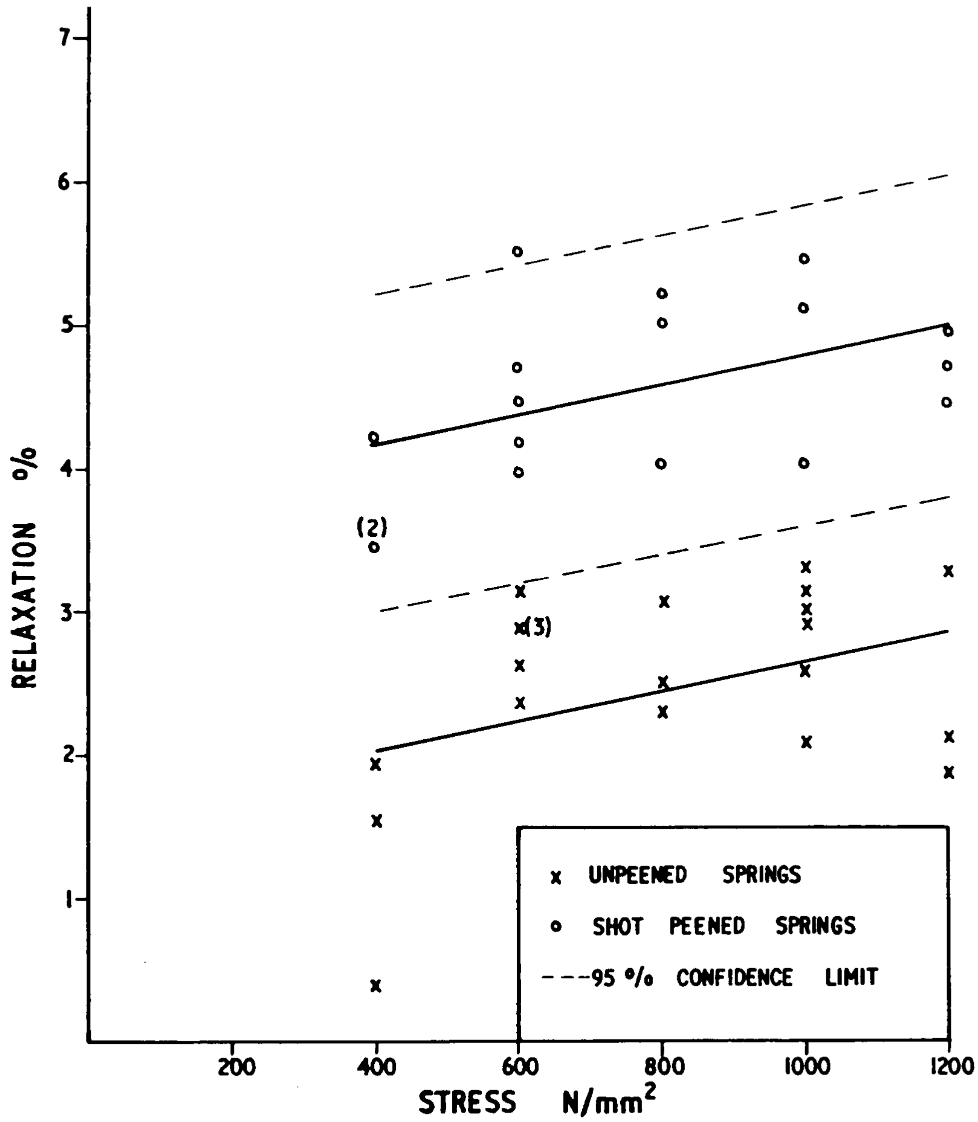

FIG. 9 RELAXATION OF 18 % Ni Co Mo MARAGING STEEL SPRINGS WITH STRESS AT 300°C (120 HOUR TESTS)

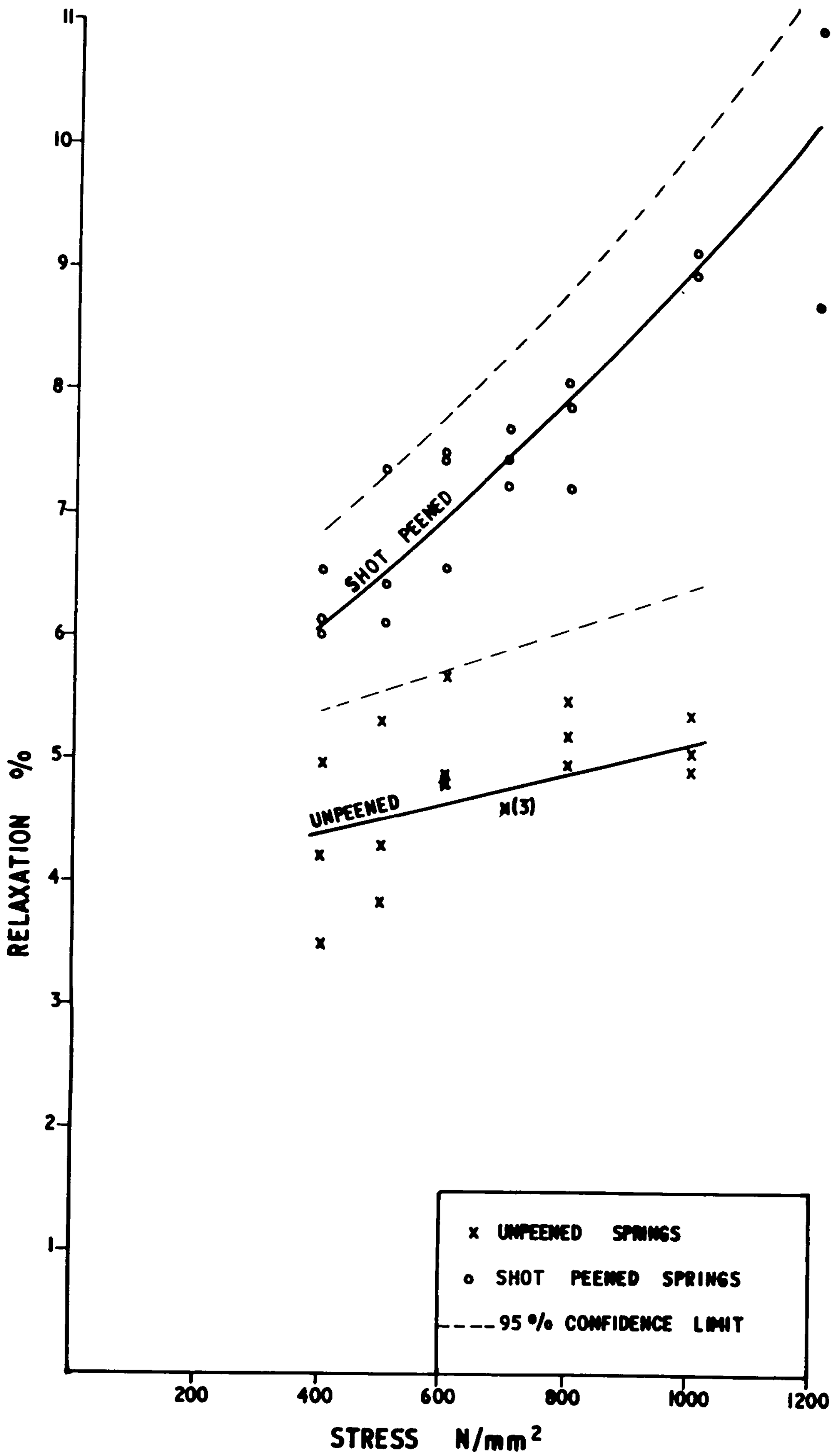

FIG. 10 RELAXATION OF 18 % Ni Co Mo MARAGING STEEL SPRINGS WITH STRESS AT 350°C (120 HOUR TESTS)

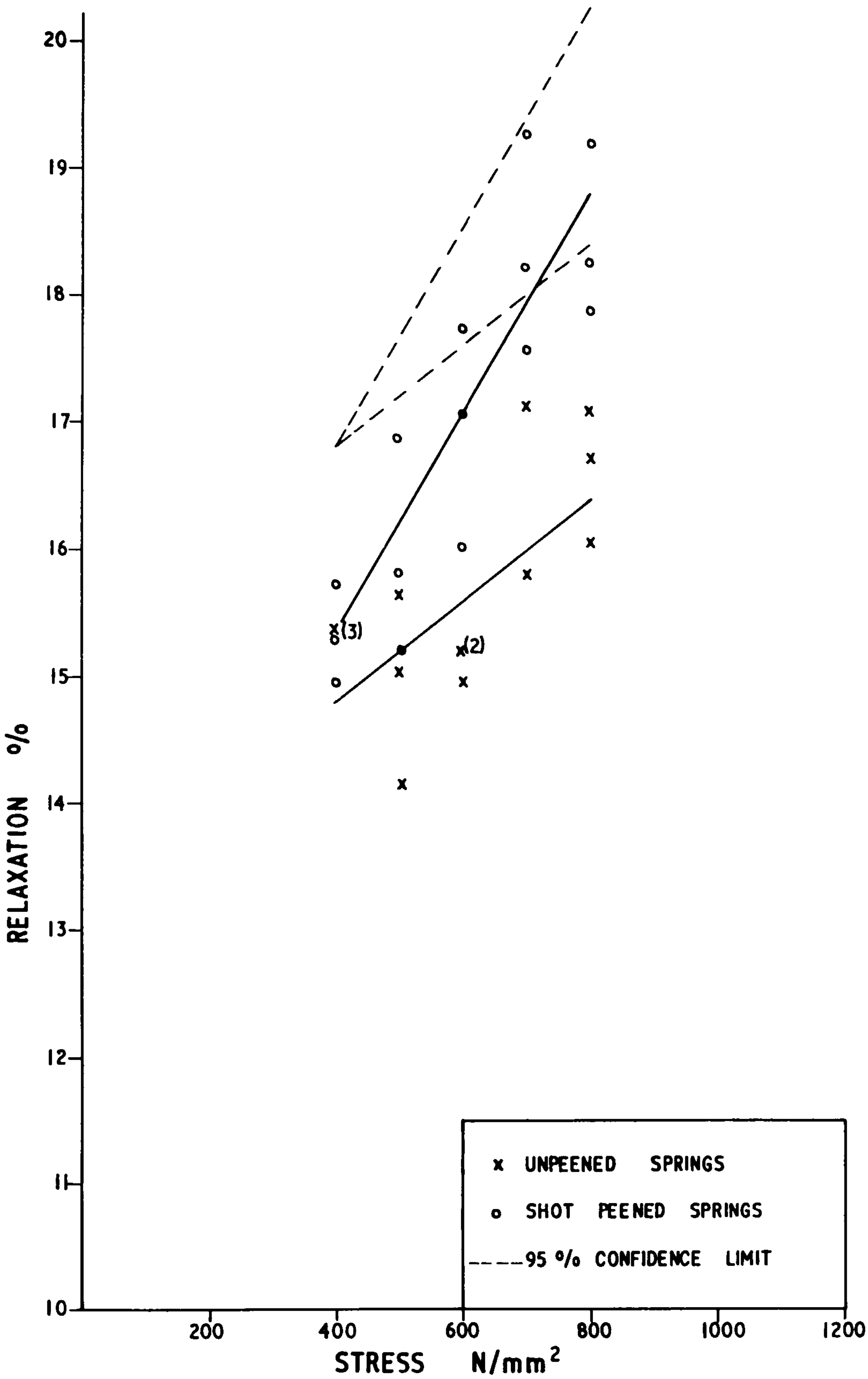

FIG. 11 RELAXATION OF 18 % Ni Co Mo MARAGING STEEL SPRINGS WITH STRESS AT 400°C (120 HOUR TESTS)

FIG. 12 Three Point Bending Jig for Stress Relaxation of Strip

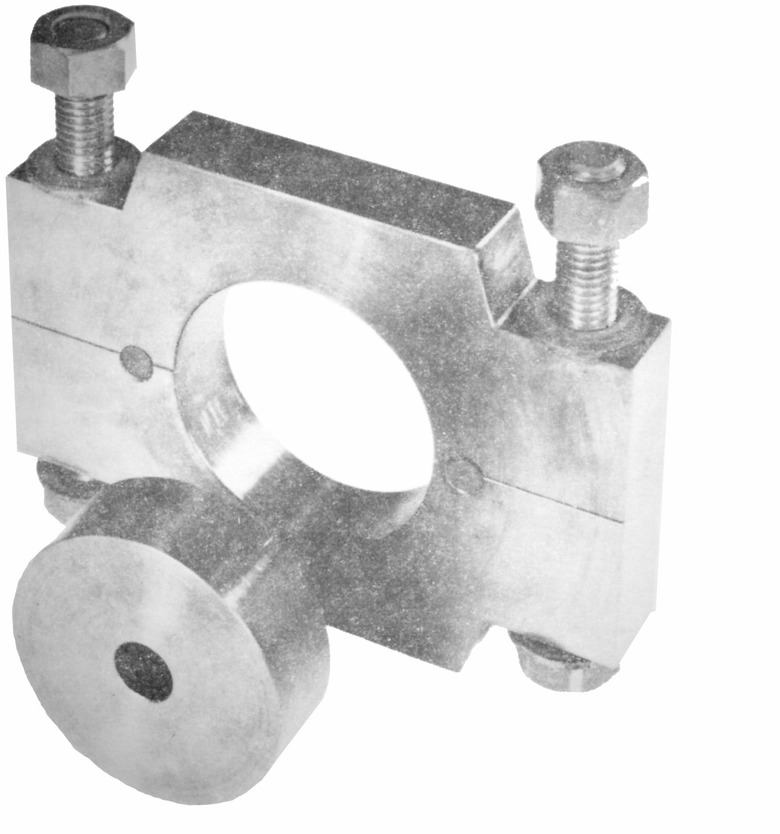

FIG. 13 Stress Relaxation Jig with Constant Curvature used for Testing Maraging Strip