THE SPRING RESEARCH AND MANUFACTURERS' ASSOCIATION

THE FATIGUE AND RELAXATION BEHAVIOUR OF HELICAL COMPRESSION SPRINGS COILED FROM TYPE 301 HARD DRAWN STAINLESS STEEL WIRE

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SUMMARY

The influence of low temperature heat treatment on S301 stainless steel wire has been evaluated, and an optimum treatment of 30 minutes at 400°C determined.

The fatigue and relaxation properties of S301 springs in both shot peened and unpeened conditions have been investigated and compared with the corresponding properties of some other stainless materials.

Results for both peened and unpeened springs showed S301 wire to have poor relaxation properties in comparison to most of the viable alternative materials. The fatigue properties of the S301 springs were similar to those of En 58A and did not show the improvement which would have been expected from the higher tensile strength of the material.

Hence, it would appear that S301 is most suitable for use where slightly higher tensile strength is more important than good relaxation and/or fatigue properties.

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1. INTRODUCTION

The majority of hard drawn stainless wire used in the spring industry is based on the well-established 18Cr/8Ni composition. Such wire is normally specified to BS 2056: En 58A(1). However, since the tonnage of hard drawn stainless wire for springs is not particularly large when compared with that used for other engineering purposes, most wire has a chemical composition more in keeping with the general engineering steel specification BS 970: 302S25(2). This means, in general, that most hard drawn stainless wire has a composition close to 18Cr/9Ni.

Generally, solution treated material of an 18% Cr, 8% or 9% Ni content is fully austenitic. However, on hard drawing a deformation induced transformation to martensite may occur, giving a mixed martensite/austenite structure. Reduction of the levels of Cr and Ni to about 17% and 7% respectively (with a corresponding decrease in Mn content), as in 301S21(3) i.e. S301, increases the martensite content. This results in hard drawn S301 wire having a greater tensile strength than similarly hard drawn En 58A wire. A fuller discussion of the effects of chemical composition and deformation on the austenite/martensite transformation is given in the appendix to this report.

In this investigation the influence of low temperature heat treatment (LTHT) on various properties of S301 stainless steel wire has been evaluated. Once an optimum LTHT had been determined, fatigue and relaxation properties of S301 springs were studied in more detail and compared with those of springs produced from En 58A and a few other stainless spring materials.

2. MATERIALS

Type 301 (17/7) hard drawn stainless steel wire of 2.61 mm diameter was used for this programme of work. The chemical composition is given in Table 1, along with the composition range for comparable specifications.

3. SPRING DESIGN AND MANUFACTURE

Helical compression springs were coiled from the S301 wire, to the spring design detailed in the table below, using a Torrington 115A single point coiling machine.

SPRING DESIGN

Spring Parameter	Magnitude
Wire diameter (mm)	2.61
Mean coil diameter (mm)	21.3
Total coils	5.5
Active coils	3.5
Free length after optimum LTHT (400°C) and prestressing (mm)	43.7
Solid stress (N/mm^2)	1315
R_m (as received) (N/mm^2)	1880

After coiling, batches of springs were stress-relieved in a Wild Barfield air circulating furnace at temperatures of 300, 350, 400, 450 and 500°C for thirty minutes, and then end-ground. These springs were then subjected to a variety of tests as described in parts A and B below.

PART A DETERMINATION OF OPTIMUM LOW TEMPERATURE HEAT TREATMENT (LTHT) FOR S301 WIRE AND SPRINGS

A1 TENSILE PROPERTY DETERMINATIONS

Tensile tests were carried out on a vertical Amsler multi-range tensile testing machine which used a pressure sensitive transducer to detect changes in load applied, in conjunction with an extensometer of 50 mm gauge length, the results being automatically displayed on an x-y plotter.

Duplicate tests, and in some cases up to four tests, were made on the as-received wire and also after LTHT's ranging from 150°C to 500°C.

A2 SPRING PROPERTY DETERMINATIONS

A2.1 Free Length Measurements

The effect of different low temperature heat treatments (LTHT's) on the subsequent change in free length with prestressing was investigated, using six springs for each stress-relieving temperature. LTHT's of 30 minutes duration were used, at 50°C intervals between 350°C and 500°C. Springs in the as-coiled condition were also used for comparison purposes.

The springs were individually identified prior to testing in accordance with a paired 't' test design(4,5) so that any small differences in free length occurring with prestressing could be detected.

A2.2 Fatigue Testing

Fatigue testing was carried out on a forced motion multiple station fatigue testing machine operating at 25 Hz. The maximum and minimum lengths necessary to give the required stress range were determined by load testing the springs(6).

Fatigue tests were carried out on springs which had been given a LTHT of 300, 400, or 500°C for thirty minutes, together with a set of as-coiled springs. Before testing, all the springs were prestressed to solid twenty times (preliminary trials had indicated that 20 scrags were necessary to achieve complete stability in these springs).

In all the tests, the initial stress was maintained at 100 N/mm², with the springs being tested at two maximum torsional stress levels, namely 600 and 800 N/mm². Fatigue tests were carried out using between eight and eleven springs for each of the LTHT temperatures investigated.

A2.3 Relaxation Testing

Stress relaxation tests were carried out on S301 springs at 300°C for 168 hours using the standard 'nut and bolt' assembly(7,8). The outside diameter of each spring was measured using vernier calipers, and individual loads (P, in N) for the appropriate initial torsional stresses (τ, in N/mm^2) were calculated using the standard expression:-

$$P = \frac{\pi d^3 \tau}{8DK} \qquad \text{..........} \quad (1)$$

where

d = wire diameter (mm)

D = mean diameter (mm) = (outside diameter - wire diameter)

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

$c = \frac{D}{d}$

Before relaxation testing, the compressed length resulting from the initial calculated load (L_o) was measured using a spring load tester. After 168 hours at temperature, the springs were allowed to cool before being load tested to the same compressed length so that the new load (L_F) could be determined.

The % relaxation, or loss in load, is then given by:

$$\%\ \text{relaxation} = \frac{L_o - L_F}{L_o} \times 100\% \qquad \text{..........} \quad (2)$$

Since it was considered likely that the optimum LTHT for relaxation would be similar to that found for En 58A (18/9) material(6), relaxation tests were performed on springs which had been stress-relieved at 350, 400, 450 and 500°C for thirty minutes. All the springs were prestressed to solid twenty times before testing. Five springs were tested at each of the initial stresses, 300, 600 and 800 N/mm^2 for each LTHT condition.

A3 RESULTS AND DISCUSSION

A3.1 Chemical Composition

The American Type 301 specification is covered by the British 301S21 specification(3) for strip materials (see Table I). This is very similar to the British En 58A specification(1). The chemical composition of the S301 wire studied falls within the limits of both 301S21 strip and En 58A wire specifications, but is clearly a better fit to the former specification.

Although the S301 and En 58A specifications are very similar, it is generally found that S301 material has a 17Cr/7Ni composition, whereas En 58A is typically 18Cr/9Ni (Table I). Steels with these Cr and Ni contents are nominally austenitic at room temperatures(23), but under heavy deformation, as in wire drawing, some transformation to martensite occurs(25). The amount of martensite formed is greater for a steel with a lower alloy content, such as S301.

The effect of alloy content on the formation of martensite on cooling(24) or on deformation(26) has been studied and regression equations derived. These equations enable predictions to be made of the temperature of austenite transformation to martensite, with or without deformation. Such predictions of temperature are illustrated in the table below. The S301 and En 58A analyses of Table I have been used, with N content for both alloys taken as 0.03 wt.%.

Material	Cooling Transformation Temperature Ms (°C)	Deformation Transformation Temperature Md_{30} (°C)
S301	-60	+33
En 58A	-58	+13

The equations from which these values are derived are given in the appendix to this report, together with a fuller description of the effect of alloy content on the austenite/martensite transformation temperature.

It can be seen from the above table that, whereas under cooling conditions the two alloys have almost identical transformation temperatures, on deformation the S301 transforms at a higher temperature. Obviously, the higher the deformation induced transformation temperature, the greater the amount of martensite formed at working temperatures.

Therefore, from consideration of the chemical composition of S301 and En 58A as typified by the examples in Table I, it would be expected that the S301 wire would have a greater martensite content than similarly deformed En 58A.

A3.2 Observed Tensile Behaviour

The as-drawn 2.61 mm diameter S301 wire had a tensile strength of 1880 N/mm^2 which is significantly higher than the as-drawn tensile strength of 1690 N/mm^2 for the 2.61 mm diameter En 58A (18/9) wire studied recently$^{(6)}$.

As described in the appendix, the strain-induced transformation from austenite to a low carbon martensite which occurs during the cold deformation of austenitic stainless steel is heavily dependent on the alloy content. As the alloy addition is reduced, the proportion of martensite formed during deformation increases, with a consequent increase in strength.

As the S301 wire studied has a lower Cr, Ni and Mn content than the En 58A wire$^{(6)}$ (see Table I), a higher strength would be expected in the S301 wire. Alternativelv, it is possible that some, or all, of this strength increase could have resulted from the S301 wire undergoing substantially greater reduction in area than the En 58A wire.

The effect of LTHT on the tensile strength and elastic properties of S301 wire can be seen in Figure 1, while the experimental data is listed in Table II. The maximum elevation in tensile strength and elastic properties occurred with stress-relieving treatments between 375 and 400°C (see Figure 1). There was a maximum increase in tensile strength with LTHT of 6%, while for the elastic properties, maximum increases of between 12 and 14% were observed. These improvements in tensile and elastic properties with stress-relief are similar in magnitude to those observed in En 58A (18/9) springs(6).

The effect of LTHT time on the tensile properties of S301 wire for LTHT's at 350, 375 and 400°C was investigated and the results are shown in Tables III, IV and V respectively. Although varying LTHT time had some slight effect on tensile properties, the differences were not large enough to be statistically significant. It is considered therefore that a 30 minute stress-relief is sufficient to give the optimum improvement in tensile and elastic behaviour of S301 hard drawn wire.

A3.3 Change in Free Length with Prestressing

The effect of cold prestressing on the free length of springs given a number of different LTHT's is shown in Figure 2.

It is clear that the absence of a LTHT before prestressing leads to more pronounced set-down than that observed for springs given LTHT's at 300°C and above. Furthermore, prestressing leads to a distinct decrease in free length whatever the LTHT condition. For LTHT's between 350°C and 500°C, although some statistically significant differences in the magnitude of the decrease in free length with prestressing were detected, it is unlikely that these will be of any practical significance. In other words, changes in LTHT temperature have only a minimal effect on the magnitude of the 'set-down' which occurs with prestressing.

A3.4 Effect of LTHT on the Fatigue Behaviour of S301 Springs

The fatigue performance of S301 springs at a number of LTHT temperatures for maximum stresses of 600 N/mm^2 and 800 N/mm^2 is shown in Figures 3 and 4 respectively.

At a maximum stress of 600 N/mm^2, normal 't' tests indicated that there were no significant differences (at the 95% level) between the various sets of fatigue data. When the maximum stress is increased to 800 N/mm^2, however, it can be seen that springs given a 500°C stress-relief had slightly lower fatigue lives than springs LTHT'd at lower temperatures.

In each case, where a comparison was drawn with the 500°C LTHT, a statistically significant difference (at the 99% level or higher) was found. It is debatable, however, whether these statistical differences will be of any practical significance.

Overall, the effect of LTHT on the fatigue behaviour of S301 compression springs is rather limited. This is similar to the situation observed with En 58A (18/9) springs in earlier work(6). There is no clear optimum stress-relieving treatment for fatigue, although at a maximum stress of 800 N/mm^2, there is a possibility that LTHT's above 400°C may cause a slight decrease in fatigue life.

A3.5 Effect of LTHT on the Relaxation Performance of S301 Springs

The influence of LTHT temperature on the relaxation properties of S301 springs, at three initial stress levels, is shown in Figure 5.

From Figure 5, it can be seen that a minimum in relaxation occurs at, or close to, 450°C for all three initial stress levels. These curves have been fitted to the data by eye. A complex curve fitting procedure might produce some slight adjustment to the curve minima, but this is unlikely to be significant.

Statistical comparisons between the sets of relaxation data obtained for each LTHT temperature were carried out. Results showed that the differences in relaxation behaviour after LTHT at 400°C and 450°C were not significant (at the 95% level), and that the difference between the relaxation data for 450°C and 500°C stress-relieving treatments was only just significant at the 95% level. To some extent, this is a reflection of the scatter in relaxation values at any one stress level. (Note:- the 95% confidence bands shown on the 300 N/mm^2 initial stress level curve on Figure 5, bring this point out). In practical terms, therefore, a LTHT between 400°C and 500°C is likely to give optimum relaxation resistance in this material, but there may be grounds for suggesting that a LTHT below 450°C might be marginally better.

The situation for S301 springs can be contrasted with the effect of LTHT on En 58A (18/9) springs(6), where a 500°C/ 30 minute stress-relief gave a distinct minimum in relaxation.

A3.6 Overall Effect of LTHT on S301 Wire and Springs

From the investigations carried out it has been shown that the tensile strength and elastic properties of 2.64 mm diameter S301 wire reach a maximum close to 400°C, while maximum relaxation resistance is likely to occur with a stress-relieving treatment at about 450°C. These improvements in elastic properties and relaxation resistance with LTHT can be explained on a similar basis to that proposed in earlier work on 18% Cr/9% Ni stainless material(6). The corresponding optimum LTHT's for the 18/9 material are 400-425°C and 500°C for tensile properties and relaxation resistance respectively. It is likely that there are some small, but nevertheless important, differences in the structure of the two materials at a level indiscernible using light microscopy, which result in these slightly different responses to LTHT. A much more detailed and sophisticated investigation would be needed to reveal these differences, e.g. use of electron microscopy.

The influence of LTHT on the fatigue behaviour of S301 springs is small, although there is a possibility that LTHT's above 400°C, for maximum stresses of 800 N/mm^2 and above, might lead to a slight deterioration in fatigue performance. Optimum fatigue performance is likely to be achieved, therefore, by stress-relieving at a temperature which gives a maximum in tensile strength, i.e. 400°C.

The loss in free length with prestressing for springs given LTHT's between 300°C and 500°C was fairly constant and no practically significant differences were detected.

As well as improving tensile and fatigue properties, the 400°C LTHT also gave a distinct improvement in relaxation resistance.

The 450°C LTHT, on the other hand, while giving maximum relaxation resistance, had a deleterious effect on the tensile and fatigue properties. Thus, an optimum LTHT of 30 minutes at 400°C was chosen for the S301 material.

PART B RELAXATION AND FATIGUE PROPERTIES OF S301 SPRINGS

B1 TORSIONAL PROPERTY DETERMINATION

Torsion testing was carried out on a horizontal multi-range Tinius-Olsen torsion testing machine. The torsional properties of the wire were determined(6) in the as-received condition and after a 400°C/30 minute LTHT.

B2 EXPERIMENTAL PROCEDURE

The optimum LTHT of 400°C for 30 minutes having been established (see Part A), the remainder of the springs were given this heat-treatment in a Wild Barfield air circulating furnace, and subsequently end-ground.

Half of the springs were then shot-peened in the Association's Tilghman Wheelabrator machine, using CS330 shot. An arc rise of 0.54 mm A2 was recorded for a 30 minute exposure. Earlier work carried out at SRAMA(9) has shown that after 30 minutes exposure with CS330 shot, optimum shot-peening coverage has been achieved. After peening, the springs were stress-relieved at 225°C for 30 minutes, previous work(10) having established this LTHT as giving the optimum balance between fatigue and relaxation properties.

All the springs were then cold prestressed to solid twenty times. (Preliminary work on this material had shown that twenty scrags were necessary to ensure complete stability in the springs).

Both the unpeened and shot peened springs were used for fatigue and relaxation tests in the manner described below.

B2.1 Fatigue Testing

Fatigue testing was carried out on a forced motion multiple station testing machine as described in A2.2 above.

Both the unpeened and the shot peened springs were tested at initial stresses of 100, 200 and 300 N/mm^2 to produce S/N curves from which modified Goodman diagrams were subsequently derived.

Springs which remained unbroken at 10^7 cycles were load tested again to determine the load necessary to give the original minimum length set on the fatigue machine (this minimum length corresponds to the maximum stress applied to the spring). The dynamic relaxation, or loss in load occurring during fatigue testing was then determined from these results.

B2.2 Relaxation Testing

B2.2.1 Time-Relaxation properties of S301 springs

Once the optimum stress-relieving treatment of 400°C for 30 minutes had been determined, it was considered appropriate to check the validity of 168 hours as a suitable test period for S301 springs.

Relaxation tests were carried out as described in A2.3 above.

Unpeened springs were tested at two initial stresses of 400 and 800 N/mm^2, using three springs at each stress level. After load testing, the springs were put into an air-circulating oven at 300°C. Sequential tests were carried out on the same set of springs, with the relaxation being determined after total times of 4, 10, 15, 36, 60, 102, 176 and 240 hours at temperature. Subsequent to this, these tests were continued to 1415 hours so that an idea of the long-term variation of relaxation with time could be determined for this material.

B2.2.2 Stress-relaxation behaviour of S301 springs

Using the same experimental technique as described in A2.3 tests were carried out on both the unpeened and the shot peened springs at temperatures of 250, 275, 300 and 350°C for 168 hour periods. At each temperature, five springs were tested at each of the initial stresses, 300, ~~450, 600~~, 800 and 900 N/mm^2.

B3 RESULTS AND DISCUSSION

B3.1 Torsional Properties

The torsional properties of the 2.61 mm diameter S301 wire, both as-received and after a 400°C/30 minute LTHT are given in Table VI.

It can be seen from Table VI that a 400°C stress-relief does improve the torsional properties, the 0.1% and 0.2% proof stresses being increased by 25 and 21% respectively. There is also a slight increase in rigidity modulus, G, of around 6%.

It is generally accepted, on the basis of earlier work at SRAMA(11,12) that the variation of torsional properties with LTHT will follow a similar trend to that observed for tensile properties, and, for this reason, a more detailed study of these properties has not been carried out on this S301 wire.

B3.2 Fatigue Properties

Fatigue data, in the form of S/N curves, for both the unpeened and the shot peened S301 springs is shown as Figures 6 to 11.

Limited life fatigue data is often represented by a straight line, particularly for martensitic ferrous materials. The majority of the data obtained for S301 compression springs, however, appeared to be better suited by a curve than a straight line. For each initial stress level, in both the unpeened and shot peened conditions, both the linear and reciprocal relationships were examined and the best fit to the data was determined using a least mean squares procedure.

Reciprocal relationships were found most adequately to represent the data in every case, except for the unpeened springs at an initial stress of 200 N/mm^2 (Figure 7). The correlation coefficients for the six curves were found to be significant at the 99% level or higher.

The 95% confidence level was determined for each set of data. In the case of the straight line relationship it was obtained using the expression:

$$95\% \text{ confidence band} = \bar{y} \pm 1.96\ Sy\ (1-r^2)^{\frac{1}{2}} \quad \text{..........} \quad (3)$$

where

$\bar{y}$ = mean of the experimental y data
Sy = standard deviation of the experimental y data
r = correlation coefficient for the mean line, as determined by the least mean squares procedure

While, for the curves which best fitted a reciprocal relationship, the 95% confidence band is given by:

$$95\% \text{ confidence band} = \bar{y} \pm 1.96\ S_R \quad \text{..........} \quad (4)$$

where

$\bar{y}$ = mean of the experimental y data
and S_R = standard deviation of the residuals of the experimental y data

S301, in common with many other non-ferritic steels, does not show a definite fatigue limit up to the endurances tested. In the shot peened condition only a small number of springs broke after 10^6 cycles, the remainder being unbroken at 10^7 cycles. From the unbroken data an estimate was made of the fatigue strength at 10^7 cycles. These estimated fatigue strengths are shown as horizontal lines on Figures 9 to 11.

Modified Goodman diagrams for both unpeened and shot peened springs, at 50% and 95% confidence levels have been derived from the fatigue curves (Figures 12 to 15).

In the unpeened condition S301 has been compared to other stainless materials in Table VII. It is clear that S301 has somewhat inferior fatigue performance to S205, 17/7 PH and Monel K500, despite the fact that it exhibits a much higher tensile strength than these alloys. The S301 showed similar properties to En 58A and to Inconel 600 (primarily a high temperature alloy chosen for its good creep and relaxation properties). Current work(13) on unpeened 2.64 mm diameter En 58A wire springs confirms the results(14) given in Table VII i.e. 100 N/mm^2 initial stress, estimated 10^7 cycles fatigue strength = 400 to 425 N/mm^2.

Table VIII makes a comparison between S301 springs and other stainless spring materials in the shot peened condition. The fatigue ratios indicate that S301, when shot peened, has a similar fatigue performance to S205, 17/7 PH and En 58A materials. However, interpretation of this data requires caution as the duration of peening and the size of shot used introduces new variables to complicate the situation.

None of the springs tested, in either the peened or unpeened conditions showed dynamic relaxation at the test temperature i.e. room temperature.

B3.3 Relaxation Properties

B3.3.1 Time-Relaxation Properties

The time-relaxation curves for the 400 and 800 N/mm^2 initial stress tests up to 1415 hours are shown in Figure 16. The curves were produced by using linear regression analysis of the experimental data in the form % relaxation vs. log time.

The correlation coefficients for both lines were significant at the 99% level of confidence.

Previous work(18) on stainless steels indicated that relaxation "equilibrium" was reached after 240 hours. ("Equilibrium" in this case refers to a stable condition such that further exposure to a given temperature will not cause any additional relaxation). The results of the present work, however, showed that this was not so for S301 material. A continuing increase in relaxation with time occurred, at both stress levels, for the entire duration of the tests.

Regression analysis was also carried out on the results of the tests up to 240 hours. Comparison of an extrapolation of the results of this analysis with the results of the longer term tests produced a maximum difference of only 1%, at 1,000 hours. This value is less than the experimental scatter of relaxation results. Thus, it can ~~be seen~~ that continuation of tests beyond 240 hours is unnecessary as extrapolation of the 240 hour data allows sufficiently accurate prediction of long term relaxation values. However, it appears that care is needed when predicting long term relaxation properties from the results of 168 hour stress-relaxation tests(B3.3.2). Such data will give relaxation values of only 70-80% of the actual relaxation at 1,000 hours.

In view of the time involved in carrying out long term tests it is probably better, from a practical standpoint, to continue to use a 168 hour test period for stainless materials, provided that the results are carefully interpreted.

B3.3.2 Stress-Relaxation Properties

Results for the unpeened and shot peened springs are expressed in Figures 17 and 18 respectively. The plots shown were fitted to a linear relationship using linear regression analysis, the correlation coefficients being in all cases significant at the 99% level of confidence. For simplicity only two 95% confidence lines are shown, the bands for the other two temperatures being of similar dimensions. The confidence lines were calculated as in B3.2 for a straight line.

The peened springs showed somewhat greater (3-4%) relaxation than the unpeened ones at all temperatures. This effect of increased relaxation after shot peening is well known(9,19,20), although the cause has not yet been elucidated.

Statistical checks showed there to be no significant difference, at the 95% level, between the 250 and 275°C sets of data for unpeened or shot peened springs. However, there is a tendency, as indicated in the figures, for the 275°C relaxation to be higher.

The relaxation at 300°C is significantly higher than that at 275°C (or 250°C) but this difference is small compared to the very large jump in relaxation found at 350°C.

The stress-relaxation plots for unpeened S301 springs at 250, 300 and 350°C are compared with the corresponding plots for En 58A(21) springs in Figure 19. The En 58A relaxation properties are significantly better at all temperatures than those of S301. The large jump in relaxation which occurs on raising the test temperature from 300°C to 350°C is much smaller for En 58A than for S301.

The stress-relaxation properties of unpeened S301 springs at 300°C are compared with those of several comparable materials in Figure 20. Details of the wire diameters, heat treatments, test durations and tensile strengths for the various materials are given in Table IX.

Although a certain amount of data is available for peened springs, variation in the peening procedure adds an extra variable which makes valid comparison of results difficult.

In the unpeened condition, at 300°C, S301 has inferior relaxation properties to Inconel 600, 17/7 PH and En 58A, but is similar to 12R10 and superior to Monel K500. Monel K500, however, is primarily intended for use in highly corrosive environments where relaxation is of minor importance. Thus, S301 has poorer relaxation performance than the common alternative materials.

B4 CONCLUSIONS

1. Despite the higher tensile strength of S301, the unpeened springs showed inferior fatigue strengths to springs coiled from S205, 17/7 PH and Monel K500. However, the fatigue strength at 100 N/mm^2 initial stress was comparable to that of En 58A and superior to that of Inconel 600.

2. In the shot peened condition the fatigue strengths of the S301 springs improved to become superior to those of shot peened S205, 17/7 PH and En 58A springs.

3. Time-relaxation tests indicated that for S301 springs, reasonably accurate prediction of long-term relaxation is possible from 240 hour tests. Data from 168 hour tests, however, should be taken as a conservative estimate of the longer term relaxation.

4. Shot peened S301 springs showed slightly greater relaxatio (3-4%) than the unpeened springs.

5. Unpeened S301 springs show significantly poorer relaxation properties than similar En 58A springs over the temperatur range 250 to 350°C.

6. At 300°C unpeened S301 showed inferior relaxation properties to Inconel 600, 17/7 PH and En 58A, but was similar to 12R10 and superior to Monel K500.

B5 RECOMMENDATIONS FOR FURTHER WORK

It would be interesting to carry on fatigue testing of this type of material to lives much greater than 10^7 cycles. This would give a better representation of the data e.g. revealing whether a fatigue limit does in fact occur. It would be useful for design purposes as giving an indication of how long term fatigue properties are related to the data from 10^7 cycle tests.

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25. Funke, P. et al "The influence of austenitic stability on the behaviour of stainless chromium-nickel steels during cold working." DEW Techn. Ber. 1969, 9, p. 370-397.

26. Angel, T. "Formation of martensite in austenitic stainless steels - effects of deformation, temperature and composition". JISI 1954, 177 pt. 1, p. 165-174.

5. APPENDIX

SOME EFFECTS OF CHEMICAL COMPOSITION ON THE MICROSTRUCTURE OF STAINLESS STEELS

For most spring applications, the most important characteristics required of a stainless steel are corrosion resistance and good high temperature properties. For good corrosion resistance a one phase microstructure is preferable, and the presence of δ-Ferrite in an austenitic matrix should be avoided where possible.

Austenitic stainless steels may be stabilized with respect to the formation of ferrite by control of the chemical composition. Ni, C, Mn and N all act as austenite stabilizers, while Cr, Si and Mo promote ferrite formation. An indication of the size of effect exercised by these elements is shown in Table A.

The effect of chemical composition on the microstructure of stainless steels is illustrated in Figure (a)$^{(23)}$. Application of Table A and Figure (a) to the chemical composition of S301 and En 58A (Table I) predicts a fully austenitic structure for both these alloys on slow cooling to room temperature.

However, as can be seen in Figure (a) the austenite may not only transform to ferrite but also to martensite. The effect of alloying elements on the austenite/martensite transformation is different to their effect on the austenite/ferrite transformation. Almost all alloy additions tend to stabilize austenite with respect to martensite. Table B shows the effect of some common elements on the Ms point.

The transformation of austenite to martensite may be initiated in two different ways - by cooling or by deformation. The maximum temperature for martensite formation on cooling is designated the Ms point. Similarly, the highest temperature at which no martensite is formed even on very severe deformation is designated the Md point. Md is always higher than Ms.

The more highly alloyed the steel, the lower will be the Ms and Md temperatures, i.e. the more stable is the steel towards martensite formation.

Eichelman and Hull$^{(24)}$ have derived a regression equation to enable prediction of Ms temperatures to be made from chemical composition. They postulated:-

$$\begin{aligned} Ms\ (^{\circ}F) &= 75\ (14.6 - Cr) + 110\ (8.9 - Ni) + 60\ (1.33 - Mn) \\ &+ 50\ (0.47 - Si) + 3000\ (0.068 - (C + N)) \qquad \ldots\ldots\ldots\ldots \text{(i)} \end{aligned}$$

where all elements are in weight %.

Such regression equations are commonly used to relate chemical analysis and microstructure to mechanical properties. They are obtained by multiple regression analysis of experimental data.

Usually the accuracy of such expressions is sufficient to allow reasonable estimation of the value of the property involved.

While the effect of chemical composition on Md is similar to that on Ms, the quantity of martensite formed during cold working is also affected by the temperature, rate and total amount of deformation$^{(25)}$. All these factors mutually interact, e.g. the lower the deformation temperature the higher the proportion of martensite for the same total deformation. Also, on tensile deformation (as in wire drawing), more martensite will be formed than for a corresponding compressive deformation (as in rolling). As the steel is progressively reduced in cross-section the martensite content continues to rise.

The Md temperature, as defined above, is difficult to determine experimentally. Angel$^{(26)}$ defined a temperature Md_{30}, as the temperature at which 50% of martensite is formed in tension after a true strain of 0.30. The experimental results of Angel's work led to the postulation of the regression equation:-

$$\begin{aligned} Md_{30}\ (^{\circ}C) &= 413 - 462\ (C + N) - 9.2\ (Si) - 8.1\ (Mn) - 13.7\ (Cr) \\ &- 9.5\ (Ni) - 18.5\ (Mo) \qquad \ldots\ldots\ldots\ldots \text{(ii)} \end{aligned}$$

where all elements are in weight %.

In section A.3.1 equations (i) and (ii) have been used to predict the Ms and Md_{30} values for S301 and En 58A of the compositions shown in Table I. Both Ms values are about $-60^{\circ}C$, indicating that, in the solution treated condition, both types of wire should be fully austenitic at room temperature. However, the Md_{30} value of $33^{\circ}C$ for S301 is substantially higher than the $13^{\circ}C$ value for En 58A. Hence, in a similarly hard drawn condition the S301 would be expected to have a higher martensite content and, therefore, a higher tensile strength, than the En 58A.

TABLE A CHANGE IN δ-FERRITE (%) FOR 1 WT % OF ELEMENT

Element	% ferrite
Nitrogen	-200
Carbon	-180
Nickel	-10
Manganese	-1
Silicon	+8
Molybdenum	+11
Chromium	+15

TABLE B DEPRESSION OF Ms (°C) FOR 1 WT % OF ELEMENT

Element	Ms depression (°C)
Carbon	-474
Manganese	-33
Nickel	-17
Chromium	-17
Molybdenum	-21
Silicon	-11

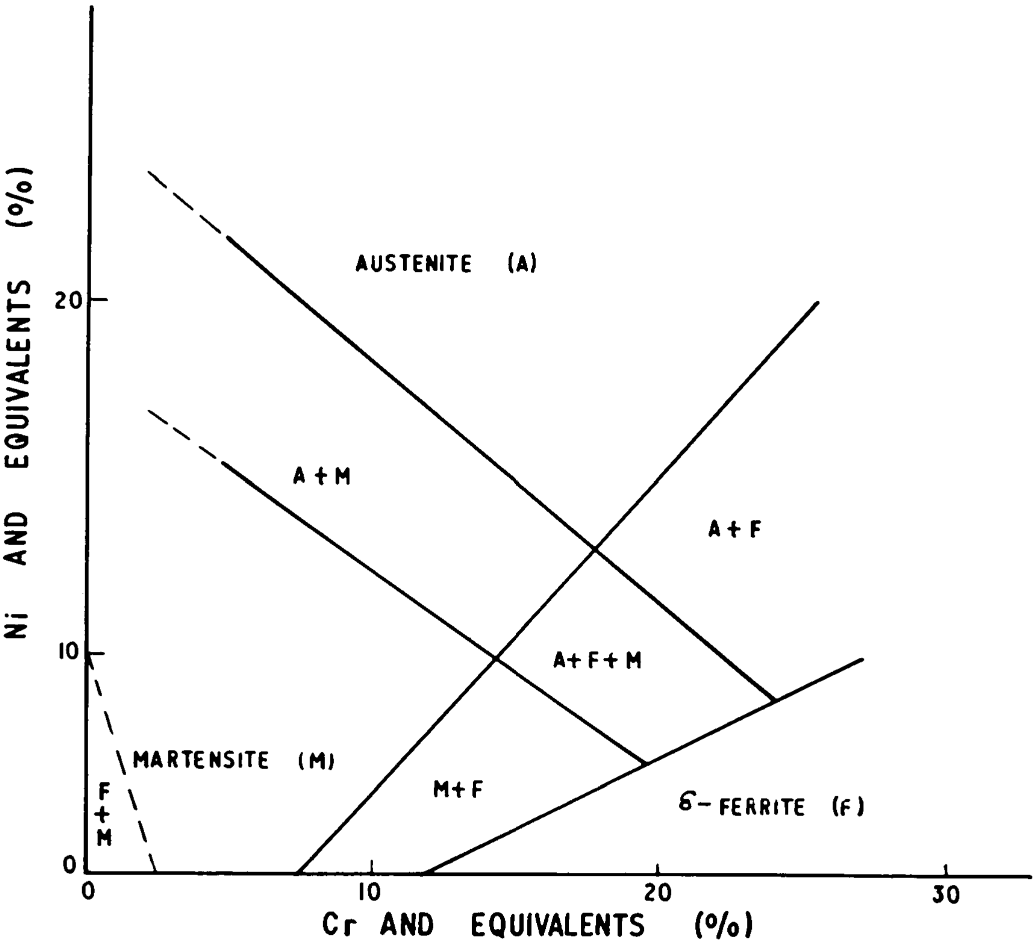

FIG. (a) STRUCTURE OF STEELS AFTER COOLING FROM ELEVATED TEMPERATURE AS DETERMINED BY COMPOSITION. (AFTER SCHAEFFLER)

TABLE I CHEMICAL ANALYSES AND SPECIFICATIONS

Material	Element (wt %)							
	C	Si	Mn	P	S	Cr	Mo	Ni
S301 actual	0.08	0.45	0.85	0.017	0.011	17.5	0.36	7.55
301S21(3) Specification	0.15 max	0.20-1.00	0.50-2.00	0.045 max	0.030 max	16.0-18.0	-	6.0-8.0
302S25(2) Specification	0.12 max	0.20-1.00	0.50-2.00	0.045 max	0.030 max	17.0-19.0	-	8.0-11.0
En58A(1) Specification	0.16 max	0.20 min	2.00 max	0.045 max	0.045 max	17.0-20.0*	-	7.0-10.0*
En58A(6) Actual	0.05	0.55	1.6	0.022	0.023	18.3	0.45	9.05

* Σ Cr + Ni $\geqslant$ 25%

TABLE II EFFECT OF LTHT TEMPERATURE ON THE TENSILE PROPERTIES OF S301 WIRE

LTHT Temperature (°C)	R_m (N/mm^2)	Proof Stresses (N/mm^2)			Limit of Proportionality (N/mm^2)
		R_p 0.2	R_p 0.1	R_p 0.05	
20 (As-received)	1880	1650	1485	1335	975
	1875	1650	1480	1335	975
150	1955	1775	1590	1405	1055
	1970	1775	1600	1425	1005
250	1960	1805	1640	1465	1080
	1955	1815	1665	1515	1140
350	1970	1825	1675	1485	1165
	1985	1835	1665	1485	1105
	1990	1830	1660	1500	1130
375	1980	1860	1700	1550	1160
	1985	1845	1660	1485	1125
400	2005	1835	1670	1485	1125
	1985	1810	1630	1460	1125
	1990	1820	1635	1435	1060
	1970	1830	1650	1470	1060
450	1965	1855	1675	1480	1105
	1985	1855	1685	1490	1105
	1965	1830	1640	1465	1065
500	1780	1690	1590	1455	1065
	1780	1705	1590	1455	1065

All LTHT's for 30 minutes

TABLE III EFFECT OF LTHT TIME ON THE TENSILE PROPERTIES OF S301 WIRE FOR A 350°C LTHT

Treatment Time (mins)	Tensile Strength R_m (N/mm^2)	Proof Stresses (N/mm^2)			Limit of Proportionality (N/mm^2)
		R_p 0.2	R_p 0.1	R_p 0.05	
30	1970	1825	1675	1485	1165
	1985	1835	1665	1485	1105
	1990	1830	1660	1500	1130
60	1950	1855	1690	1520	1170
	1975	1850	1685	1520	1170
	2000	1870	1705	1530	1145
90	1965	1825	1655	1505	1165
	1985	1870	1680	1530	1130
120	1965	1825	1655	1500	1135
	1950	1870	1705	1525	1130

TABLE IV EFFECT OF LTHT TIME ON THE TENSILE PROPERTIES OF S301 WIRE FOR A 375°C LTHT

Treatment Time (mins)	Tensile Strength R_m (N/mm^2)	Proof Stresses (N/mm^2)			Limit of Proportionality (N/mm^2)
		R_p 0.2	R_p 0.1	R_p 0.05	
30	1980	1860	1700	1550	1160
	1985	1845	1660	1485	1125
60	1985	1875	1685	1500	1075
	1980	1825	1655	1485	1100
90	2010	1850	1655	1460	1050
	2010	1975	1700	1525	1150
120	2005	1870	1695	1485	1135
	2035	1875	1675	1485	1100
	2020	1860	1685	1510	1175
	2025	1890	1735	1550	1210

TABLE V EFFECT OF LTHT TIME ON THE TENSILE PROPERTIES OF S301 WIRE FOR A 400°C LTHT

Treatment Time (mins)	Tensile Strength R_m (N/mm^2)	Proof Stresses (N/mm^2)			Limit of Proportionality (N/mm^2)
		R_p 0.2	R_p 0.1	R_p 0.05	
30	2005	1835	1670	1485	1125
	1985	1810	1630	1460	1125
	1990	1820	1635	1435	1060
	1970	1830	1650	1470	1060
60	1995	1870	1685	1500	1150
	2015	1875	1700	1525	1160
90	2005	1835	1630	1435	1000
	2010	1875	1685	1500	1085
120	2030	1860	1675	1480	1085
	2020	1855	1645	1435	910

TABLE VI TORSIONAL PROPERTIES OF S301 WIRE

Material Condition	Proof Stresses (N/mm^2)		Limit of Proportionality (N/mm^2)	Rigidity Modulus G (x 10^4 N/mm^2)
	0.2%	0.1%		
As-received	850	725	390	6.8
	870	725	390	7.0
After a 400°C/30 min LTHT	995	870	570	7.2
	1035	890	525	7.3
	1100	950	570	7.4

TABLE VII FATIGUE DATA FOR UNPEENED S301 SPRINGS AND OTHER COMPARABLE SPRING MATERIALS

Material	Material Condition	R_m (N/mm^2) after LTHT or ageing	Life N (Cycles)	Fatigue strength at initial stress of:		Fatigue ratio = Fatigue strength at zero initial stress/R_m
				0 N/mm^2	100 N/mm^2	
S301 (17 Cr/7 Ni) 2.61 mm dia	Hard drawn LTHT 400°C/½ hr	1990	10^7	340	450	0.17
En 58A(14) (18 Cr/8 Ni) 2.64 mm dia	Hard drawn LTHT 450°C/2 hrs	1735	10^7	-	430*	-
S205(15) (18 Cr/8 Ni) 1.6 mm dia	Hard drawn LTHT 450°C/2 hrs	1835	10^7	530	600	0.29
17/7 PH(16) (17 Cr/7 Ni) 1.6 mm dia	Hard drawn Aged 480°C/1 hr	1830	10^7	540	630	0.30
Monel alloy K-500(17) 2.5 mm dia	Spring temper 65% cold reduction) Aged 535°C/5 hrs	1415	10^7	435	495	0.31
Inconel alloy 600(17) 2.5 mm dia	Hard drawn LTHT 460°C/1 hr	1360	10^7	175	275	0.13

* Initial stress = 77 N/mm^2

TABLE VIII FATIGUE DATA FOR SHOT PEENED S301 SPRINGS AND OTHER COMPARABLE SPRING MATERIALS

Material	Material Condition	R_m (N/mm^2) after LTHT or ageing	Life N (Cycles)	Fatigue strength at initial stress of:		Fatigue ratio = Fatigue strength at zero initial stress/R_m
				0 N/mm^2	100 N/mm^2	
S301 (17 Cr/7 Ni) 2.61 mm dia	Hard drawn LTHT 400°C/½ hr (a)	1990	10^7	880*	925*	0.44
En 58A(14) (18 Cr/8 Ni) 2.64 mm dia	Hard drawn LTHT 450°C/2 hrs(b)	1735	10^7	-	785†	-
S205(15) (18 Cr/8 Ni) 4 mm dia	Hard drawn LTHT 450°C/2 hrs(c)	1500	10^7	680	730	0.45
17/7 PH(16) 4 mm dia	Hard drawn Aged 480°C/1 hr (d)	1830	10^7	770	830	0.42

(a) Shot peened 30 mins (S330 shot) to 0.54 mm A2, stress relieved at 225°C/½ hr

(b) Shot peened 40 mins (S400 shot) to 0.51 mm A2, stress relieved at 220°C/20 minutes

(c) Shot peened to 0.48 mm A2, stress relieved at 200°C/½ hr

(d) Shot peened to 0.48 mm A2, stress relieved at 200°C/½ hr

* Estimated values of fatigue strengths at 10^7 cycles

† Initial stress 77 N/mm^2

TABLE IX DATA FOR STRESS-RELAXATION COMPARISON (Figure 20)

Material	Material Condition	R_m (N/mm^2)	Duration of tests (hrs)
S301 (17 Cr/7 Ni) 2.61 mm dia	Hard drawn LTHT 400°C/½ hr	1990	168
En 58A(21) (18 Cr/8 Ni) 2.64 mm dia	Hard drawn LTHT 500°C/2 hrs)	1745	168
12R10(20) (18 Cr/9 Ni) 2.64 mm dia	Hard drawn LTHT 450°C/2 hrs	-	240
17/7 PH(22) (17 Cr/7 Ni) 2.29 mm dia	Hard drawn Aged 480°C/1 hr	2040	168
Monel alloy K-500(17) 2.5 mm dia	Spring temper (65% cold reduction) Aged 535°C/5 hrs	1415	300
Inconel alloy 600(17) 2.5 mm dia	Hard drawn LTHT 460°C/1 hr	1360	300

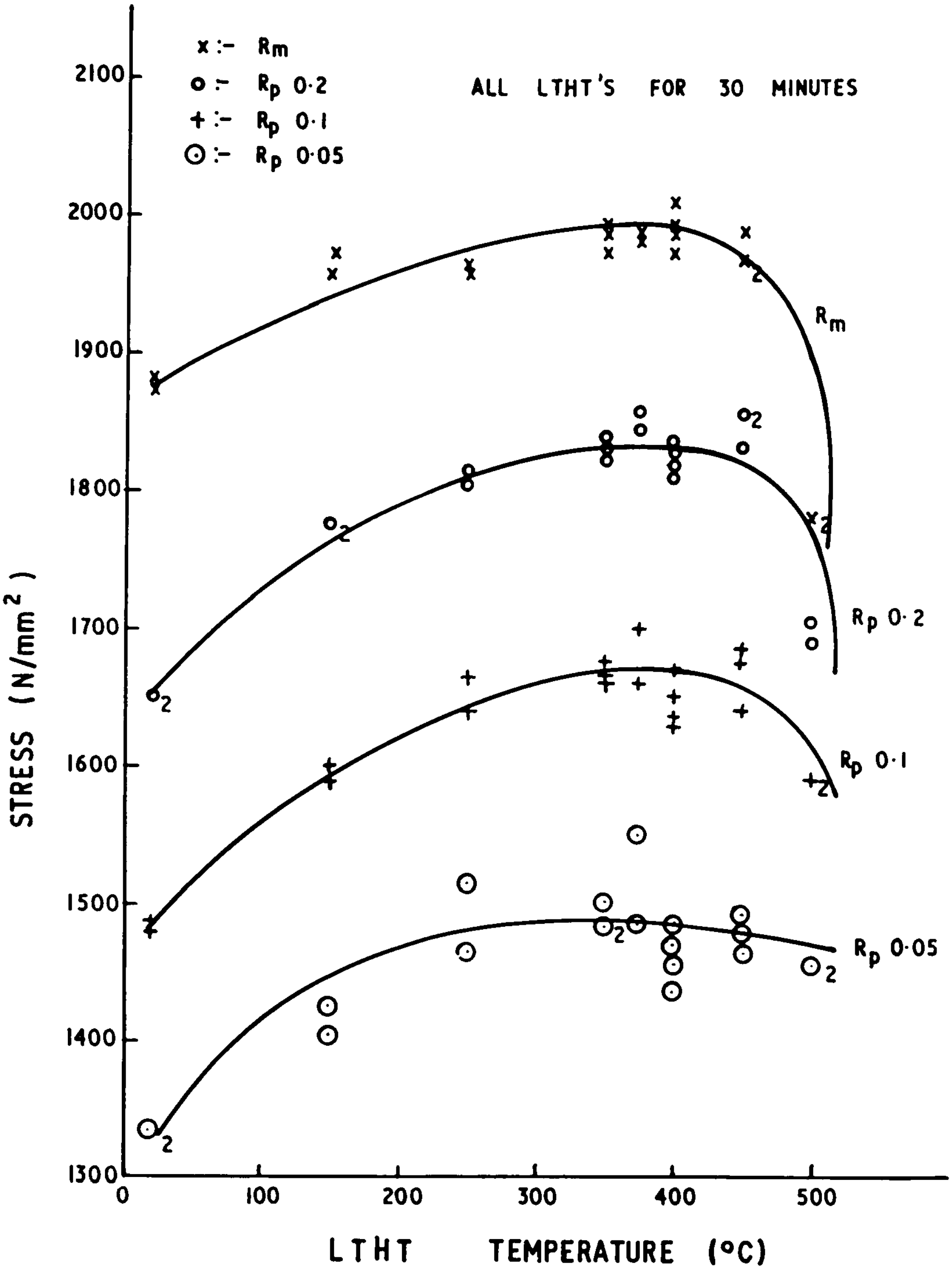

FIG. I. EFFECT OF LTHT TEMPERATURE ON THE TENSILE PROPERTIES OF S301 WIRE.

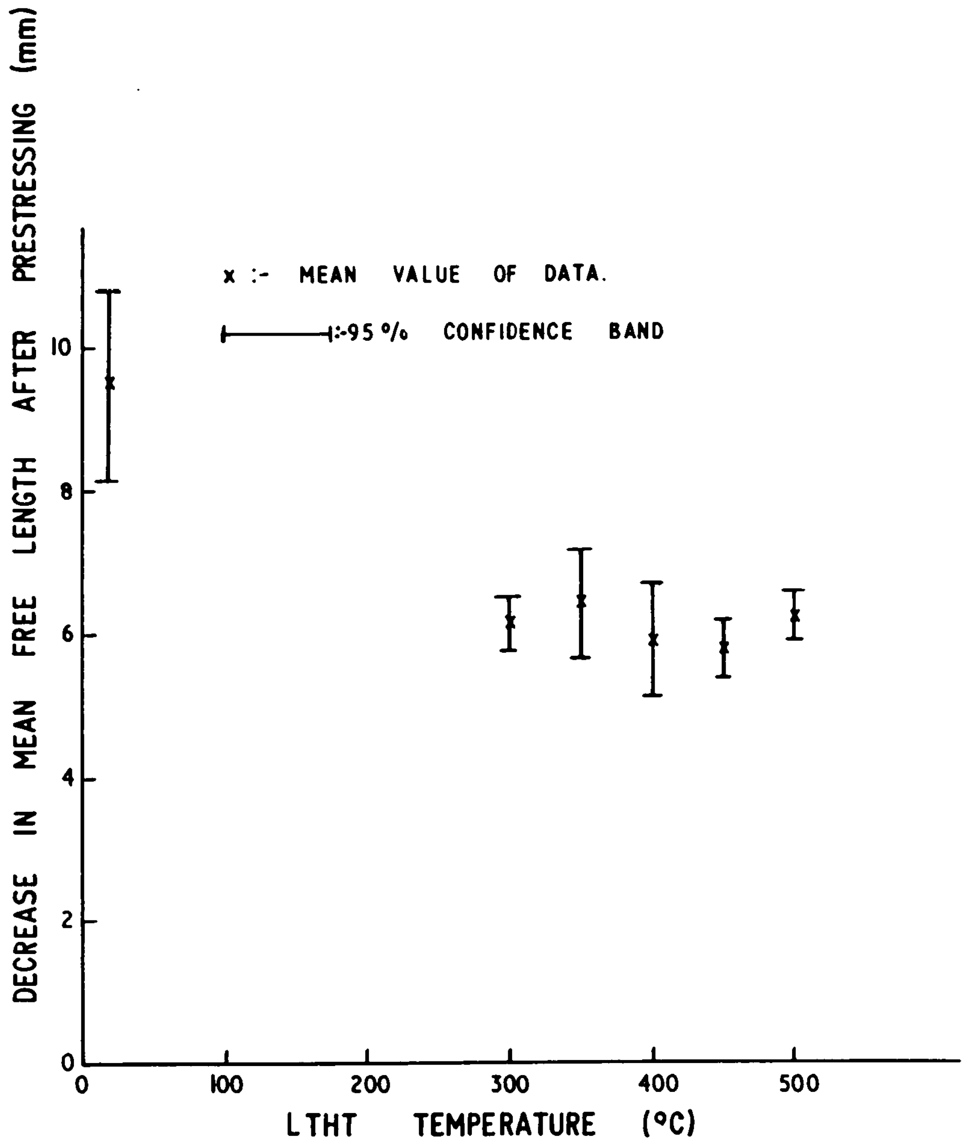

FIG. 2. CHANGE IN MEAN FREE LENGTH OF S301 UNPEENED SPRINGS WITH LTHT.

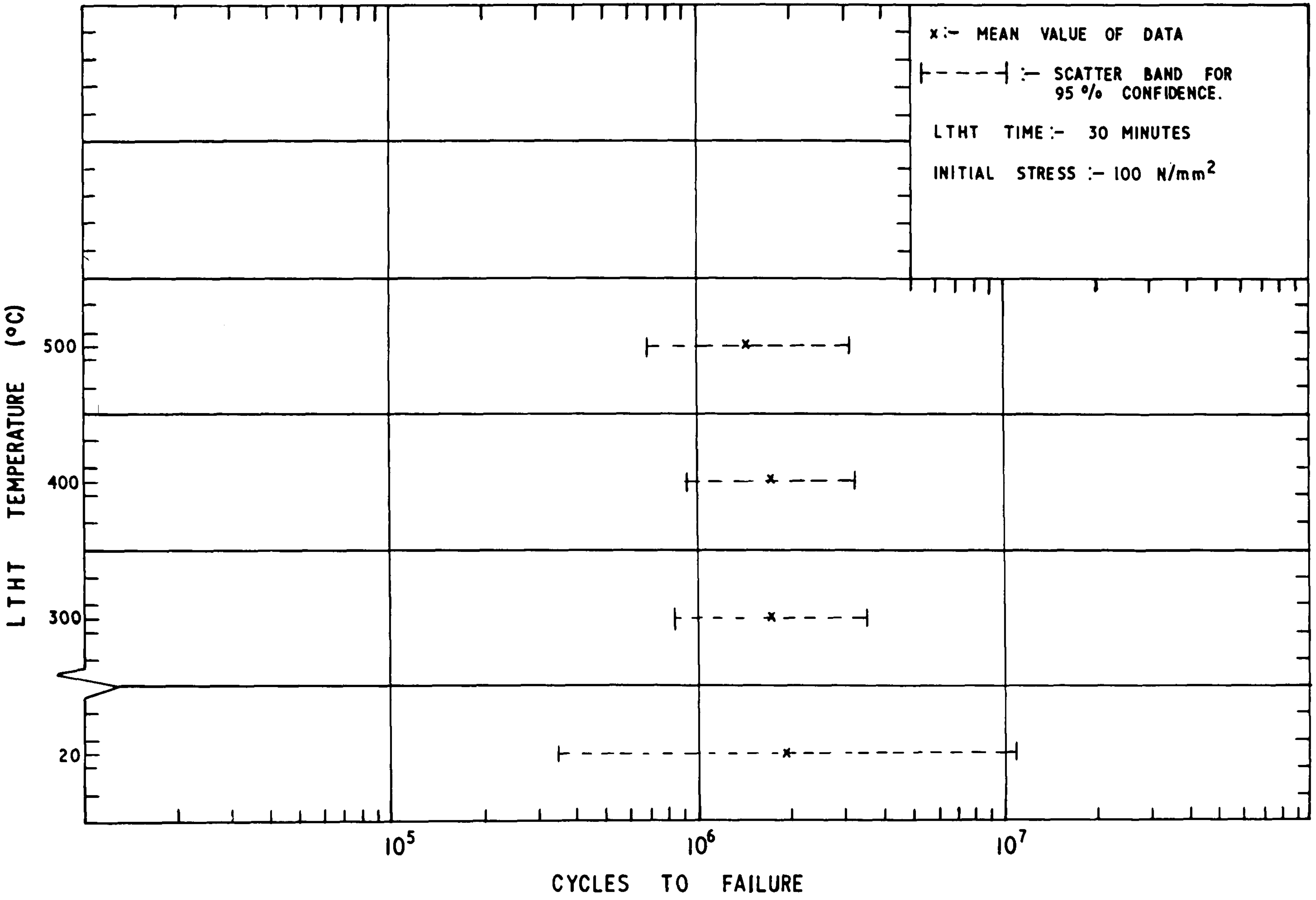

FIG. 3. EFFECT OF LTHT TEMPERATURE ON THE FATIGUE LIFE OF S301 SPRINGS, AT A MAXIMUM STRESS OF 600 N/mm^2.

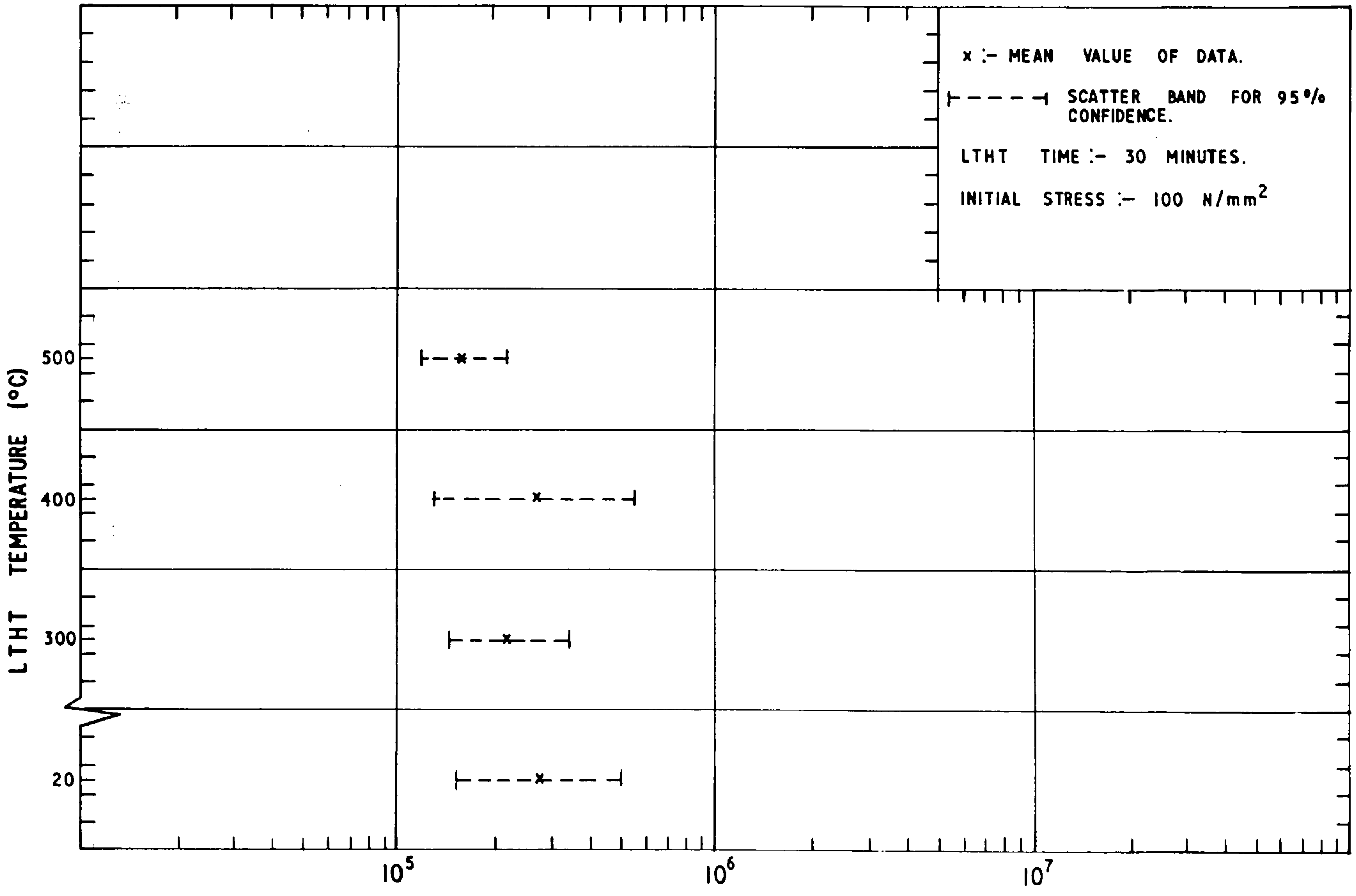

FIG. 4. EFFECT OF LTHT TEMPERATURE ON THE FATIGUE LIFE OF S301 SPRINGS AT A MAXIMUM STRESS OF 800 N/mm^2

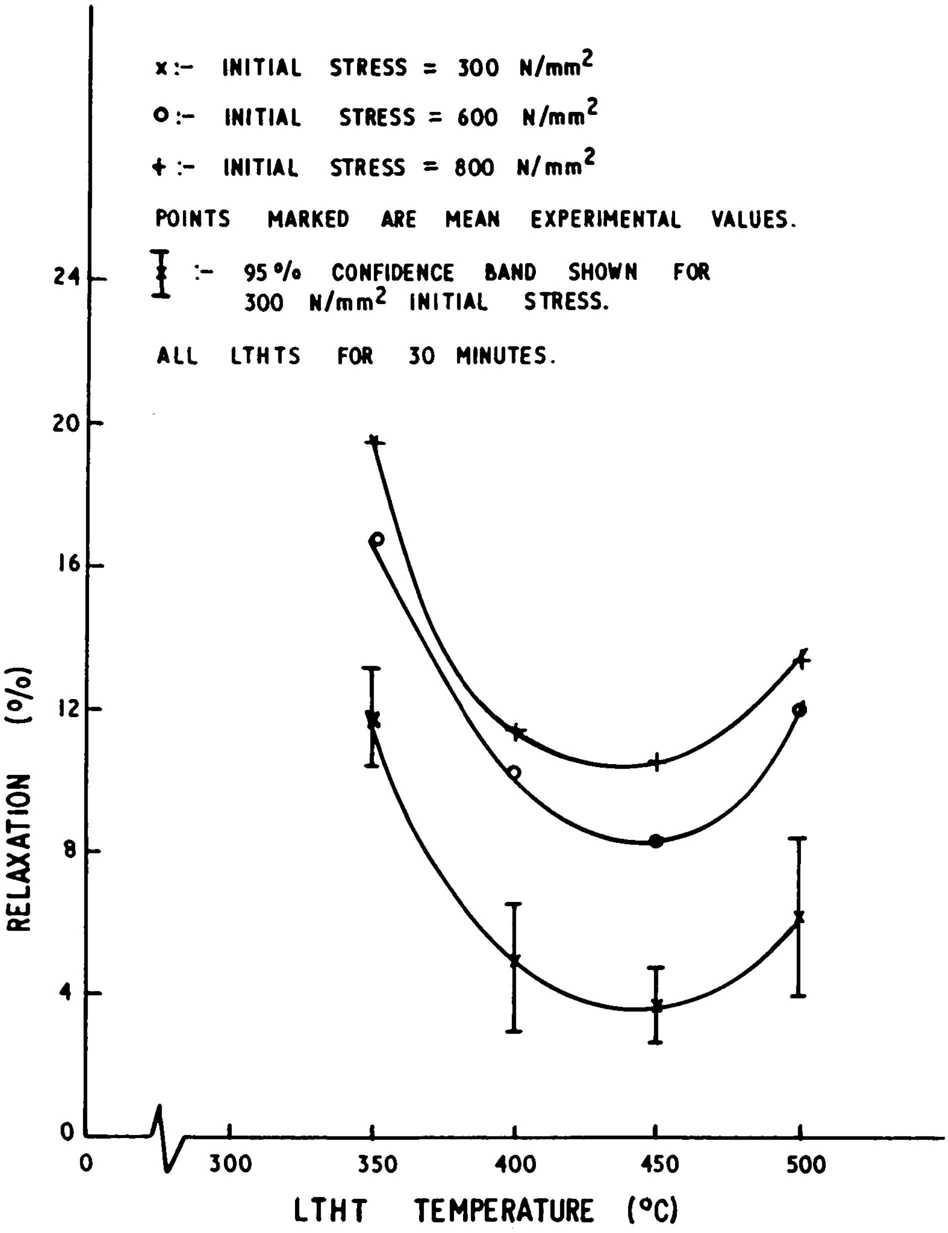

FIG. 5. EFFECT OF LTHT TEMPERATURE ON THE RELAXATION BEHAVIOUR OF S301 SPRINGS (RELAXATION TESTS AT 300°C FOR 168 HOURS)

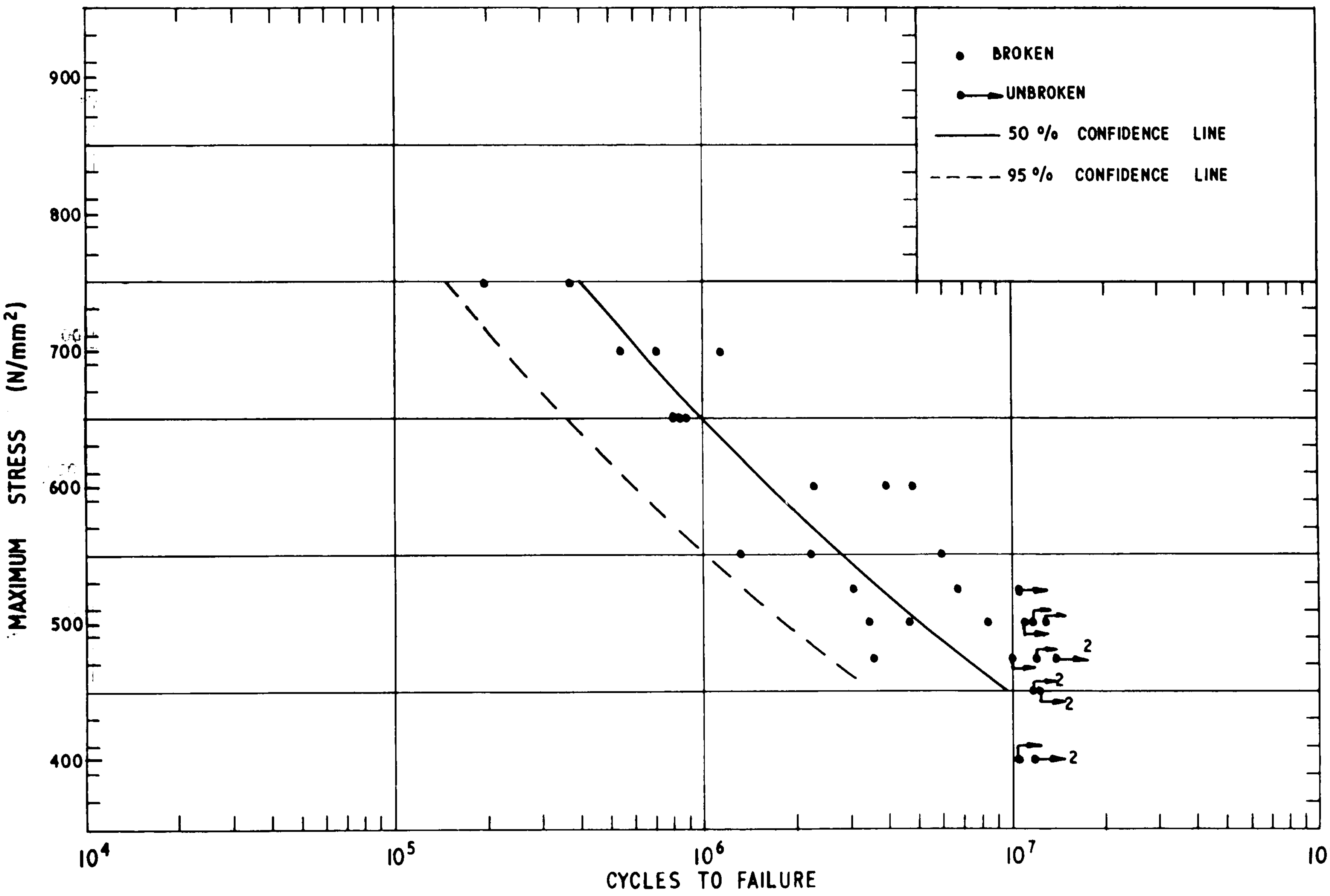

FIG. 6. FATIGUE DATA FOR UNPEENED S301 SPRINGS AT AN INITIAL STRESS OF 100 N/mm²

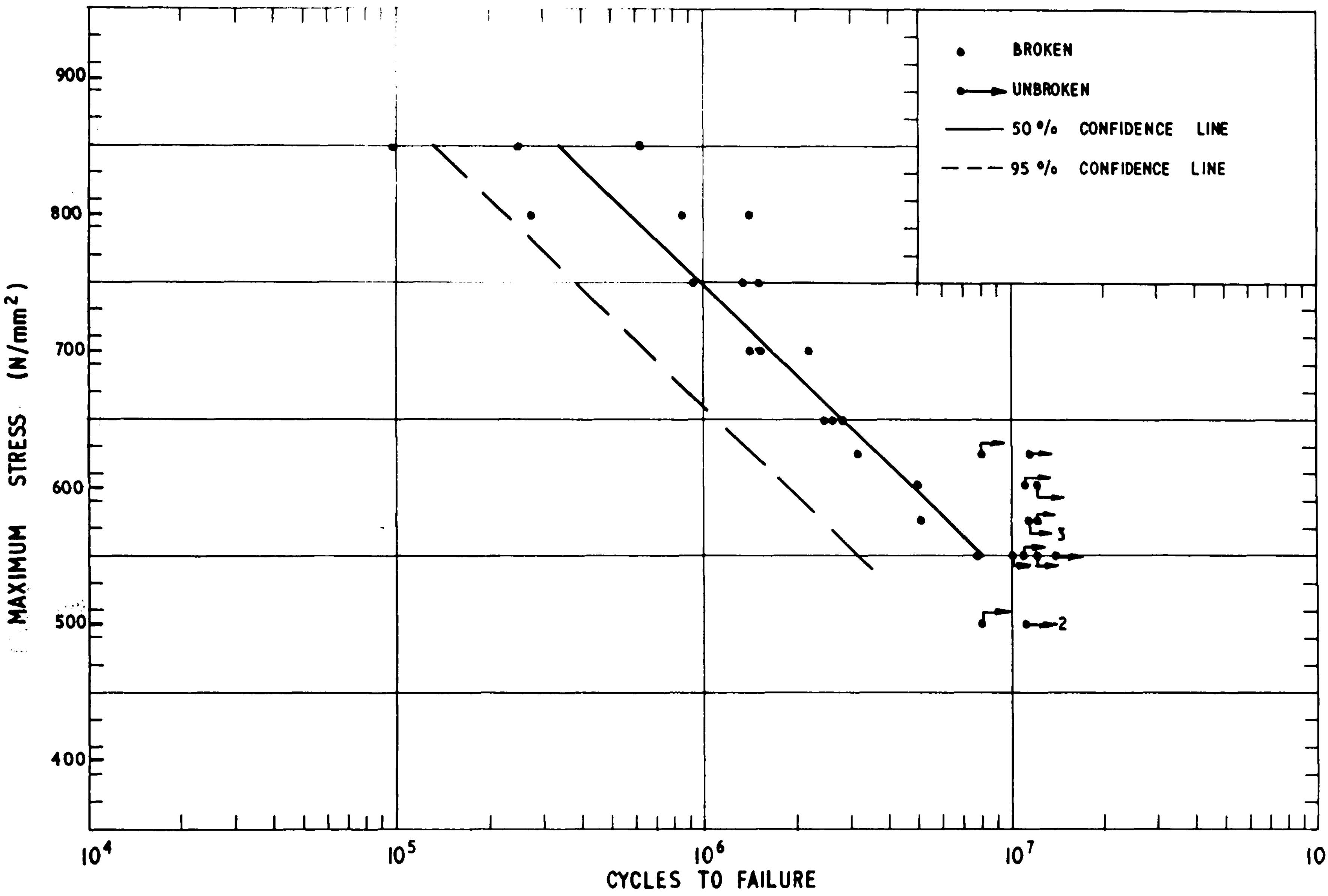

FIG. 7. FATIGUE DATA FOR UNPEENED S301 SPRINGS AT AN INITIAL STRESS OF 200 N/mm²

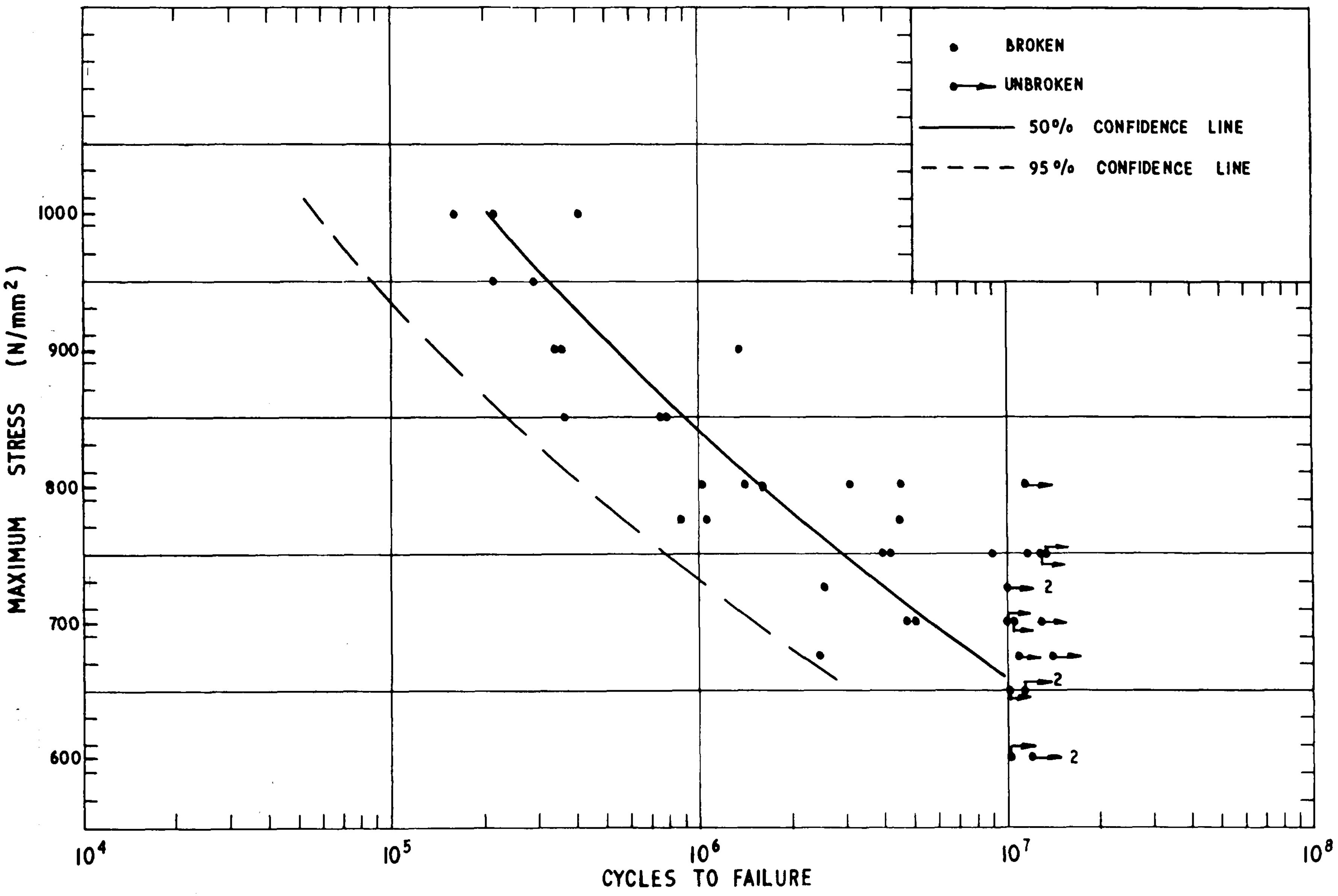

FIG. 8. FATIGUE DATA FOR UNPEENED S 301 SPRINGS AT AN INITIAL STRESS OF 300 N/mm²

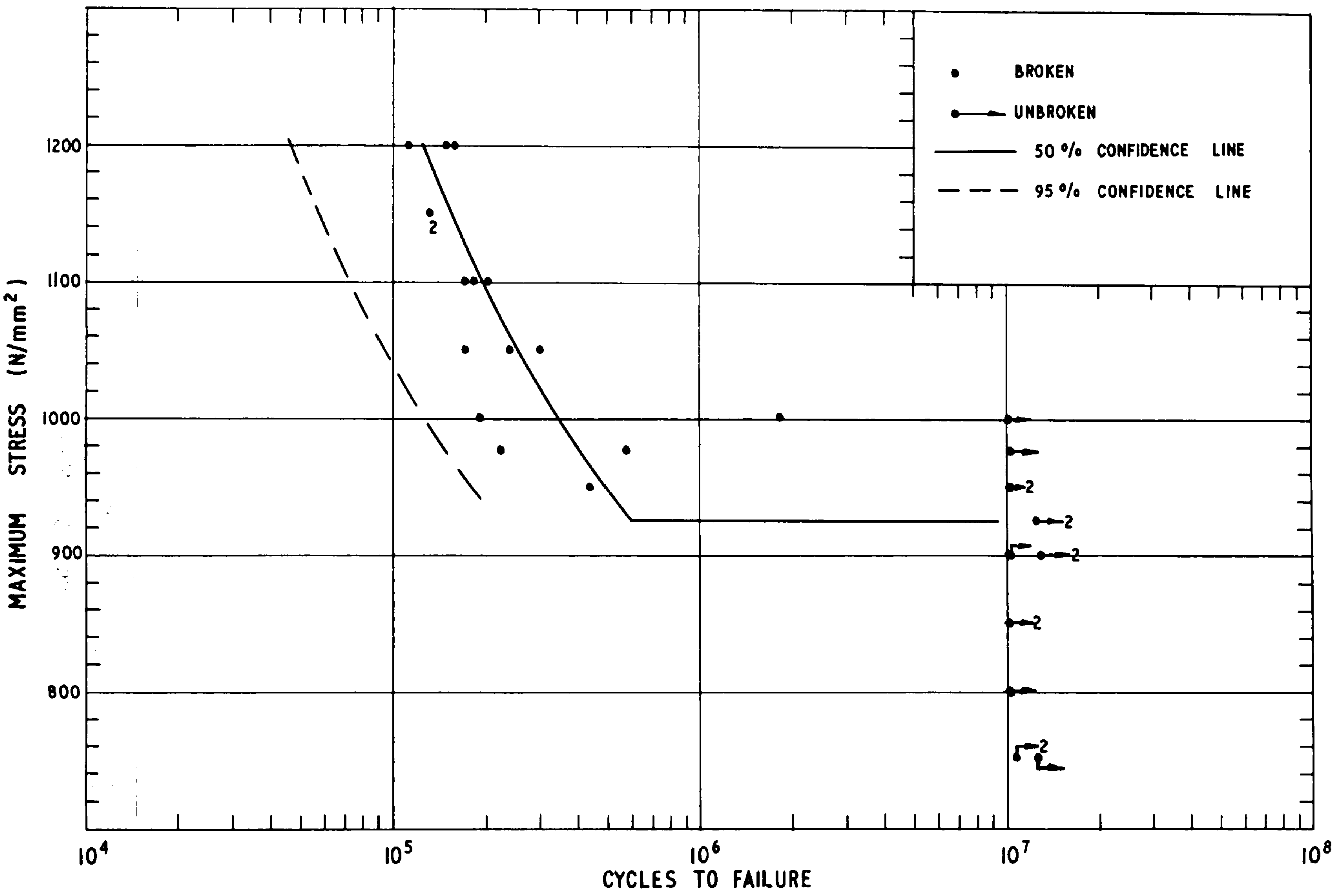

FIG. 9 FATIGUE DATA FOR SHOT PEENED S 301 SPRINGS AT AN INITIAL STRESS OF 100 N/mm^2

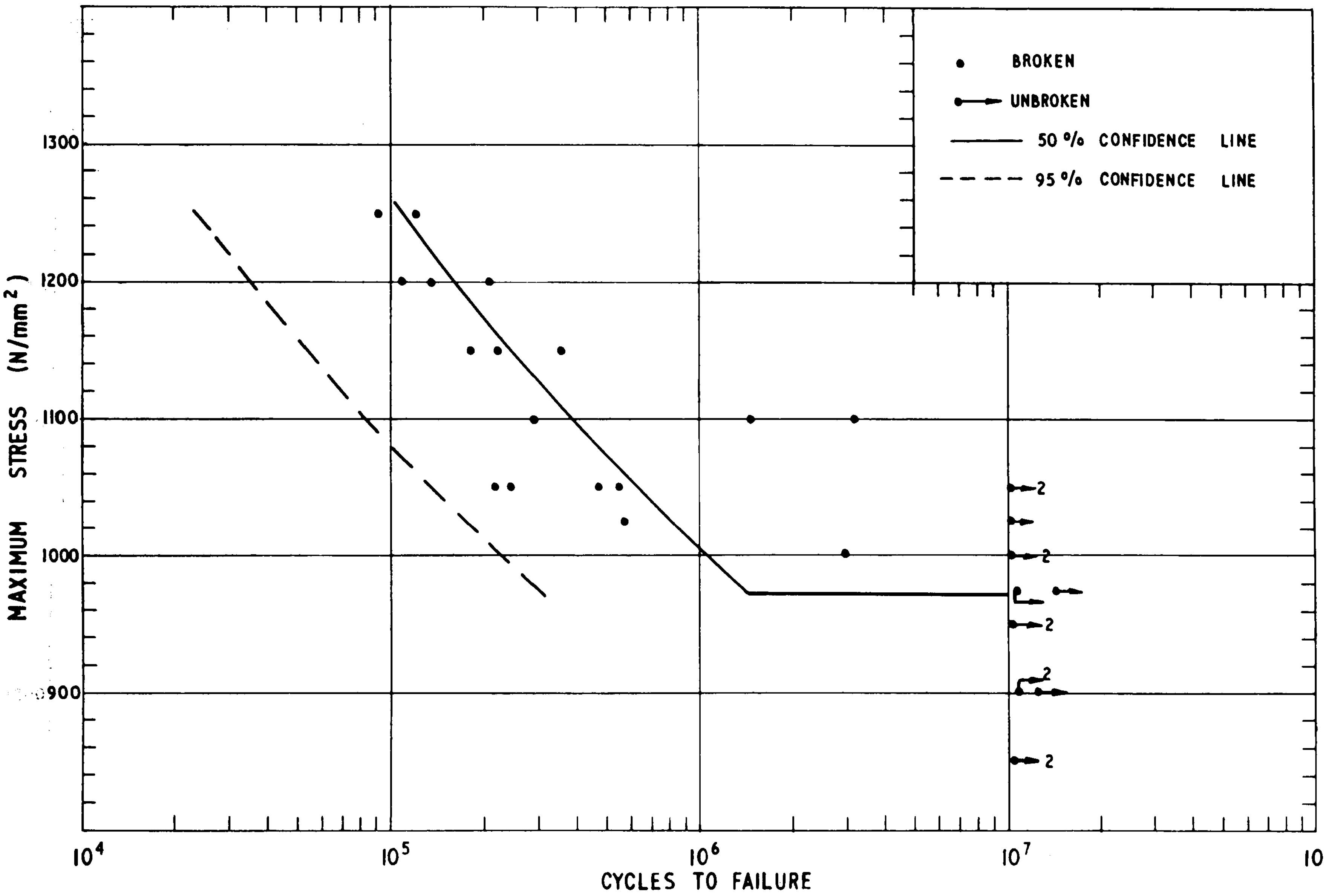

FIG. 10 FATIGUE DATA FOR SHOT PEENED S 301 SPRINGS AT AN INITIAL STRESS OF 200 N/mm²

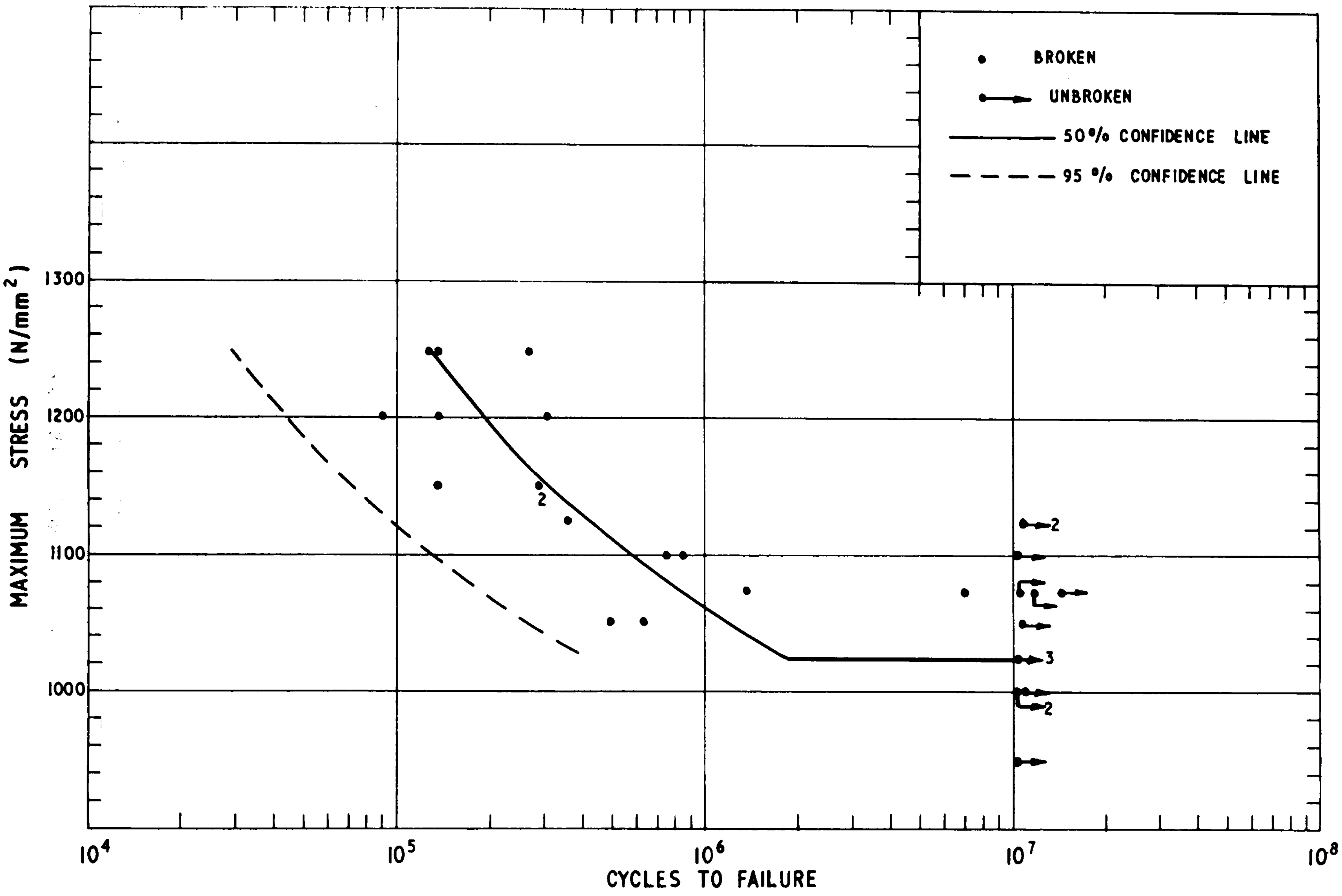

FIG.11. FATIGUE DATA FOR SHOT PEENED S301 SPRINGS AT AN INITIAL STRESS OF 300 N/mm^2

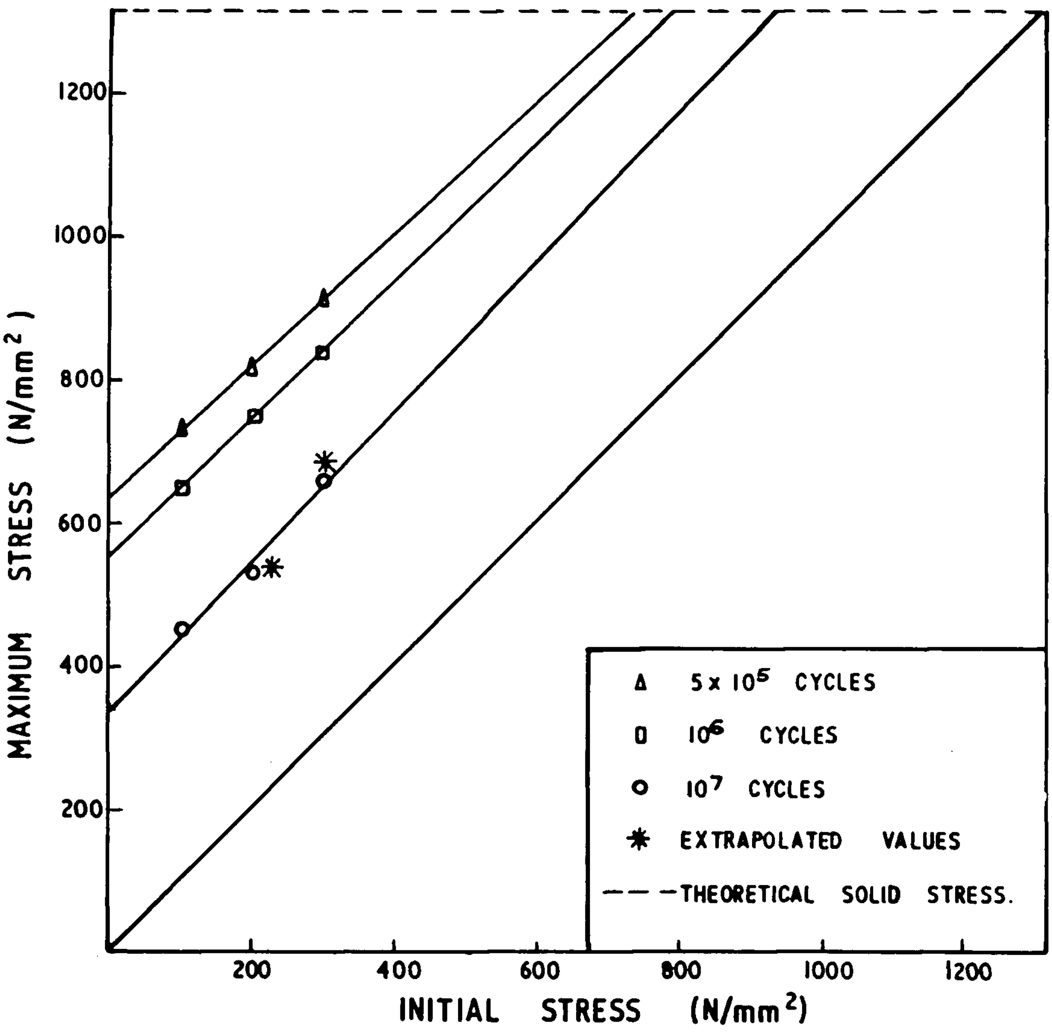

FIG. 12 MODIFIED GOODMAN DIAGRAM AT 50 % CONFIDENCE LEVEL FOR UNPEENED S301 SPRINGS.

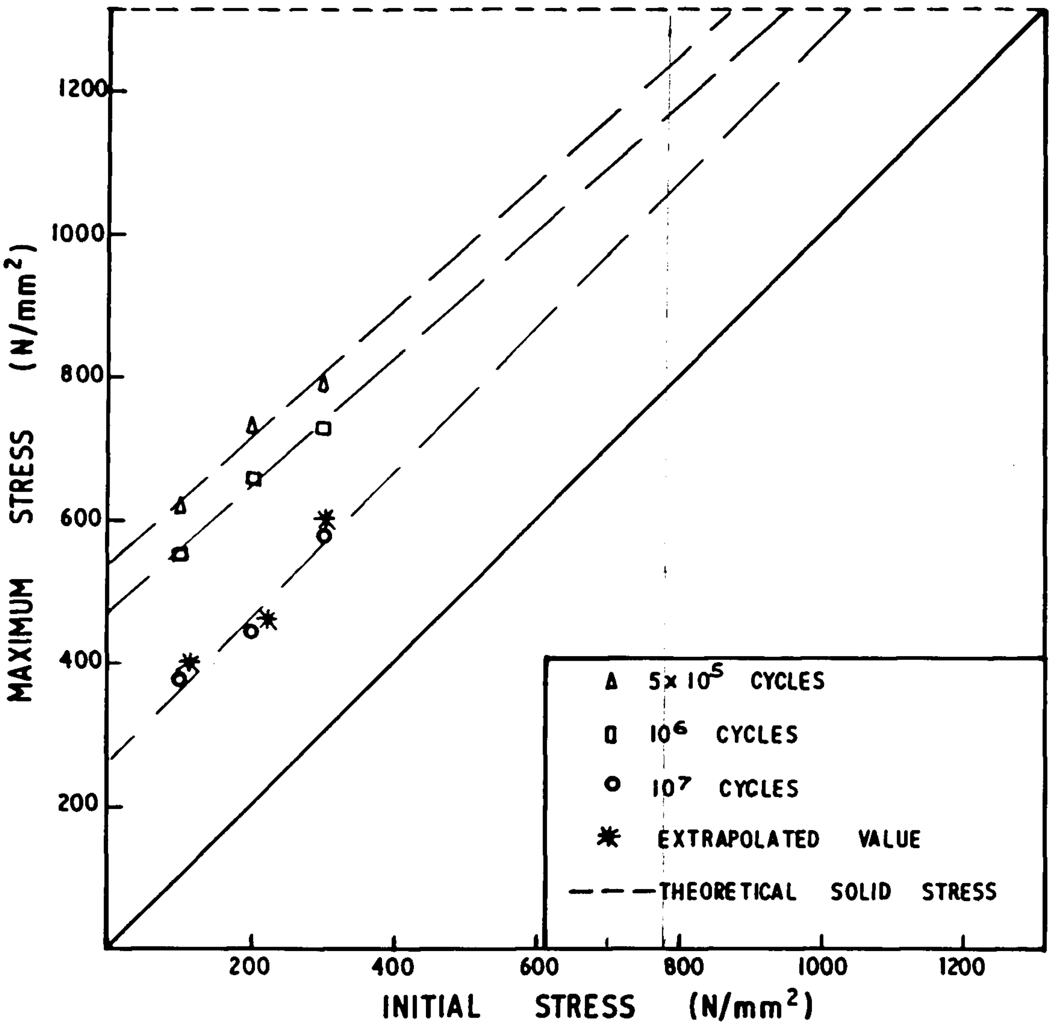

FIG. 13. MODIFIED GOODMAN DIAGRAM AT 95% CONFIDENCE LEVEL FOR UNPEENED S301 SPRINGS.

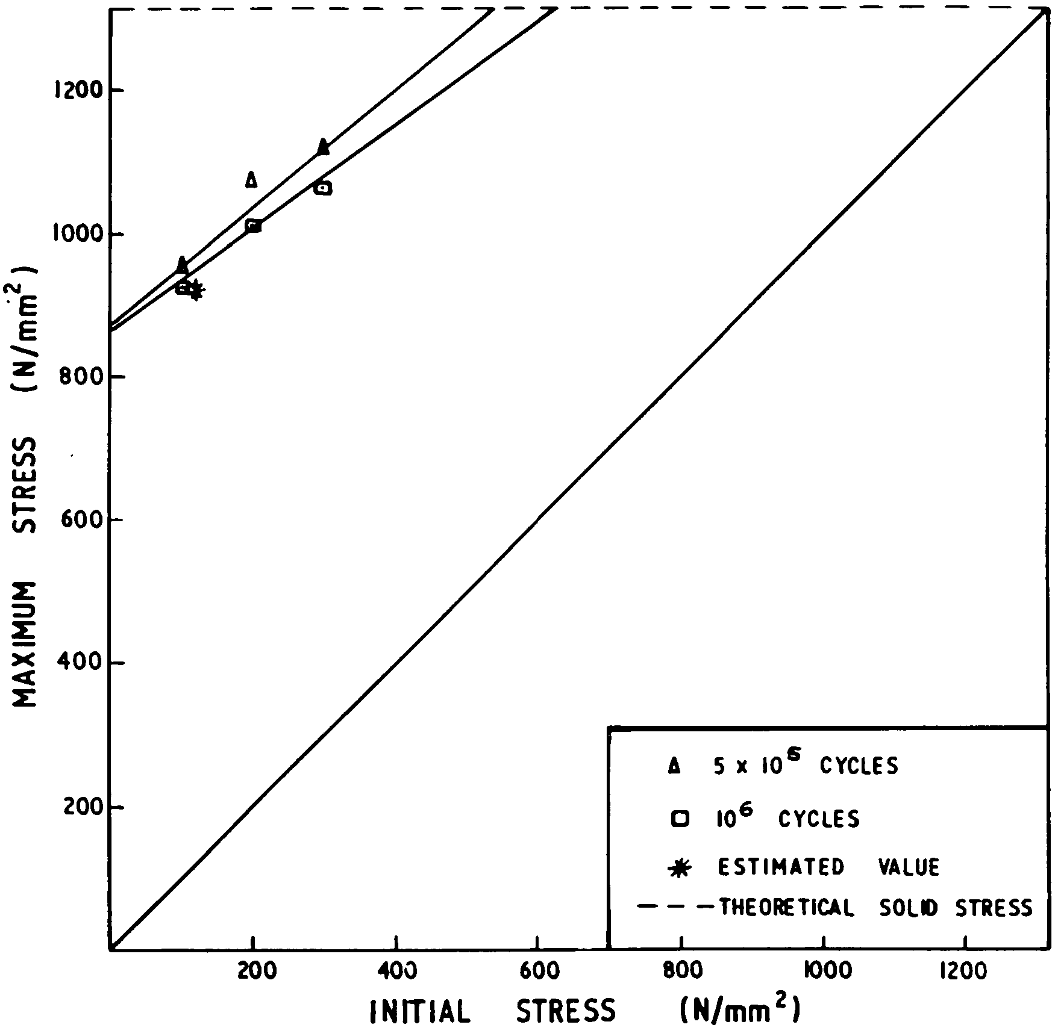

FIG. 14 MODIFIED GOODMAN DIAGRAM AT 50% CONFIDENCE LEVEL FOR SHOT PEENED S 301 SPRINGS.

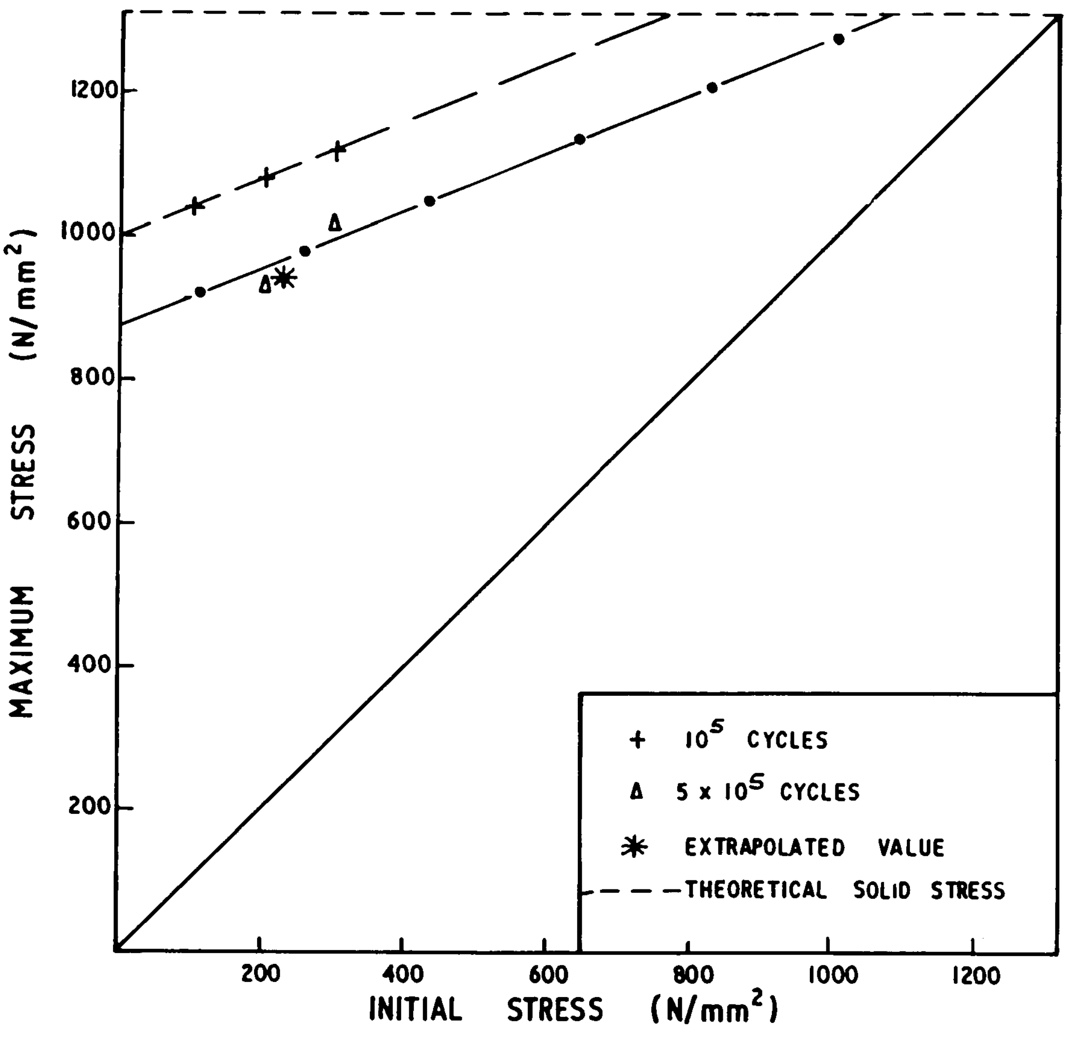

FIG. 15 MODIFIED GOODMAN DIAGRAM AT 95% CONFIDENCE LEVEL FOR SHOT PEENED S301 SPRINGS.

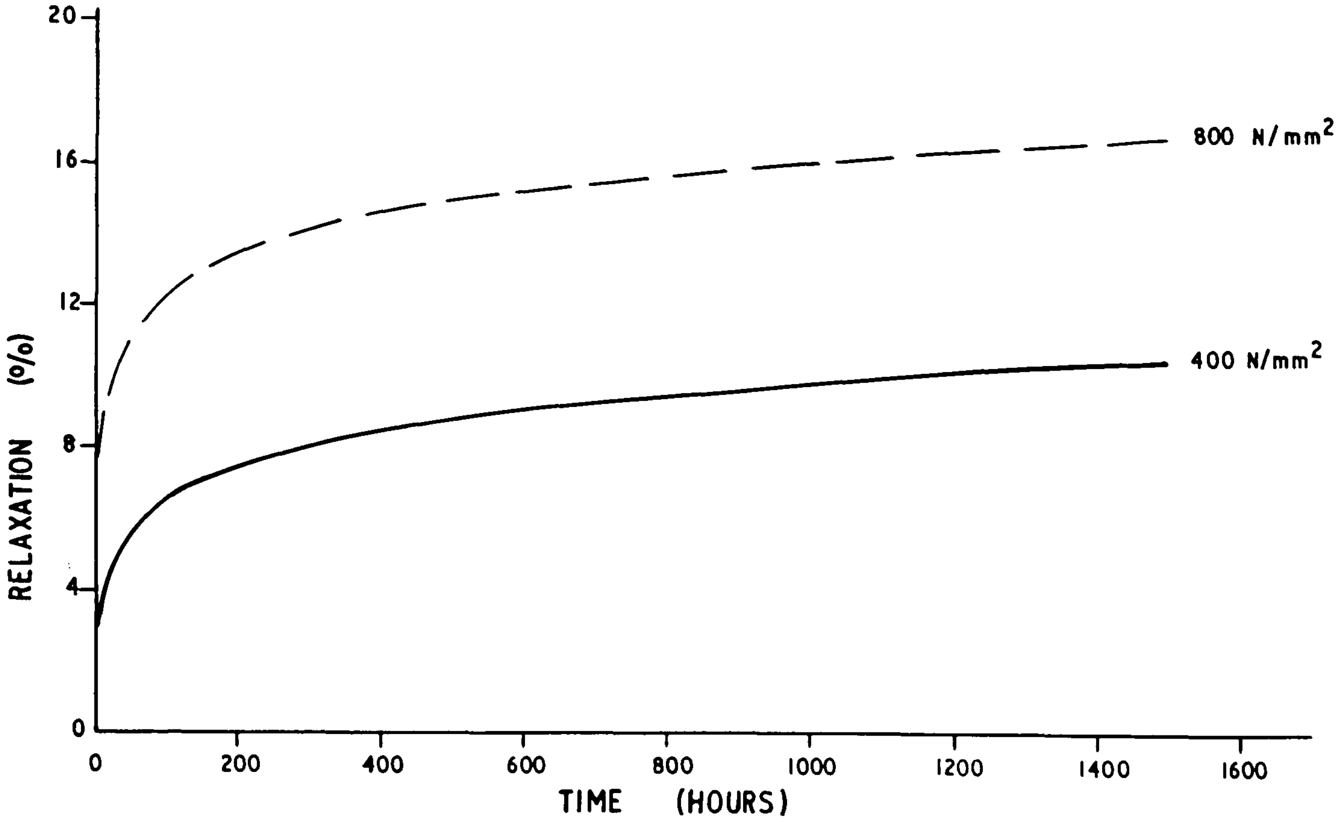

FIG. 16 TIME - RELAXATION CURVES FOR S301 SPRINGS.

(TESTS AT 300°C)

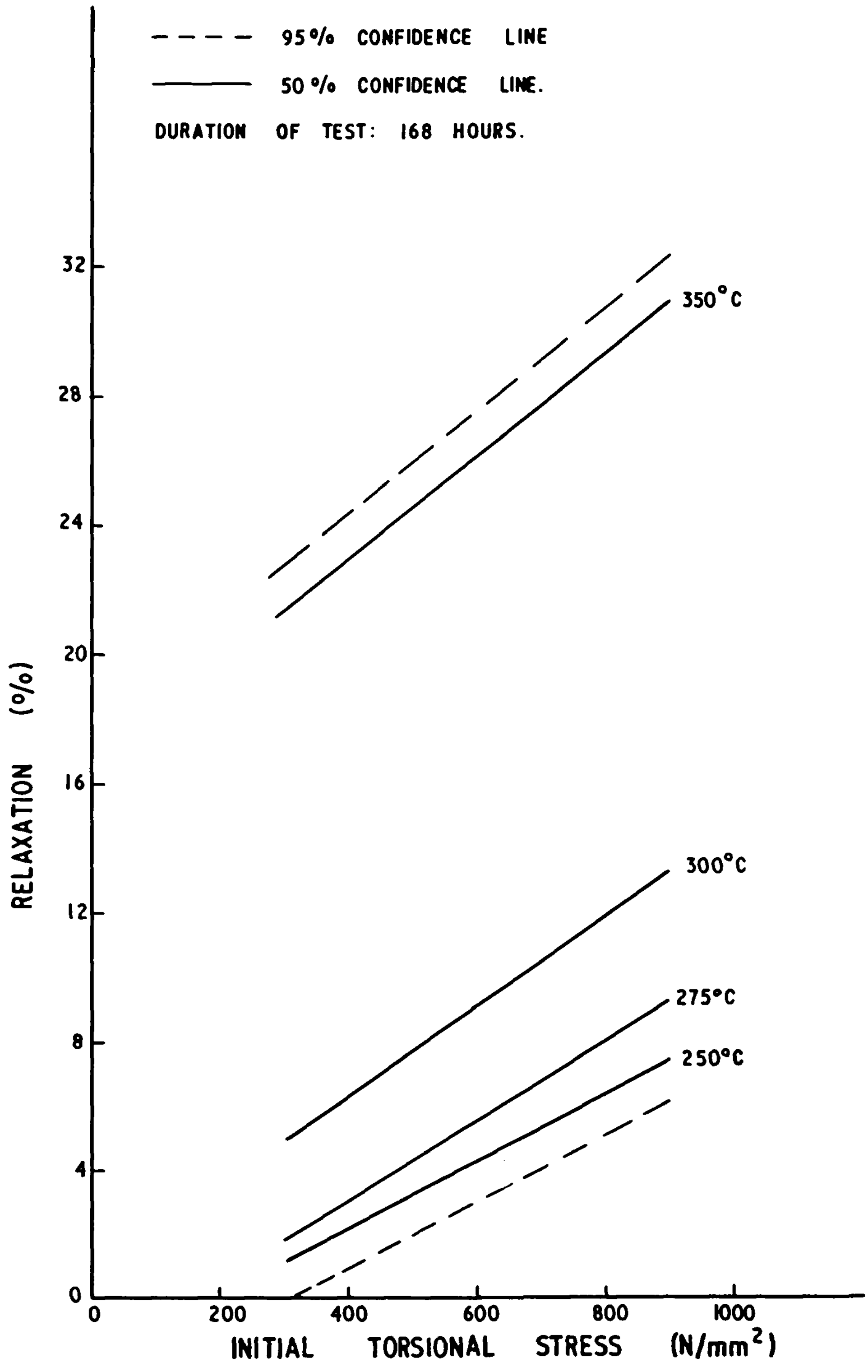

FIG. 17 STRESS - RELAXATION PLOTS FOR UNPEENED S301 SPRINGS.

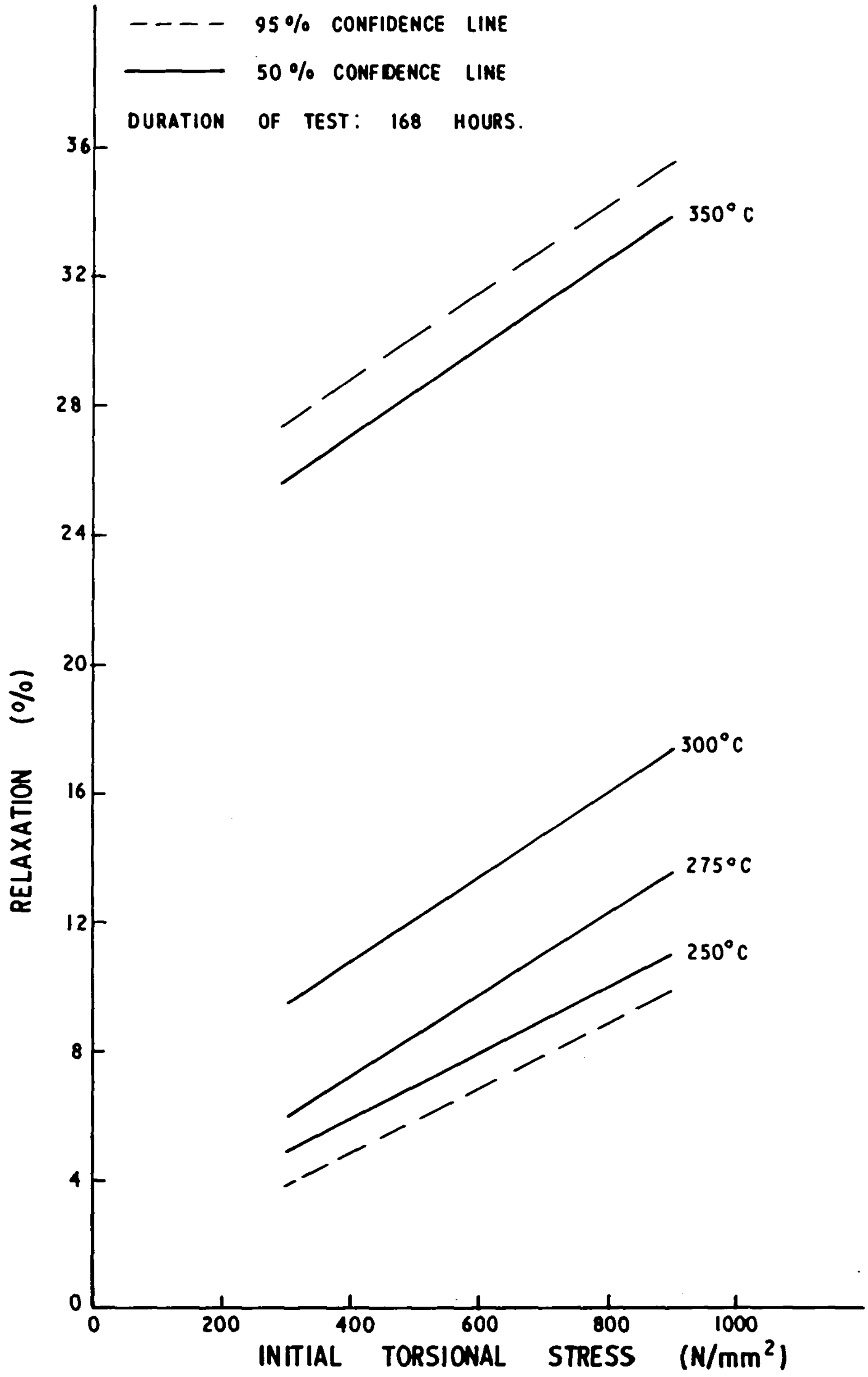

FIG. 18 STRESS - RELAXATION PLOTS FOR SHOT PEENED S301 SPRINGS.

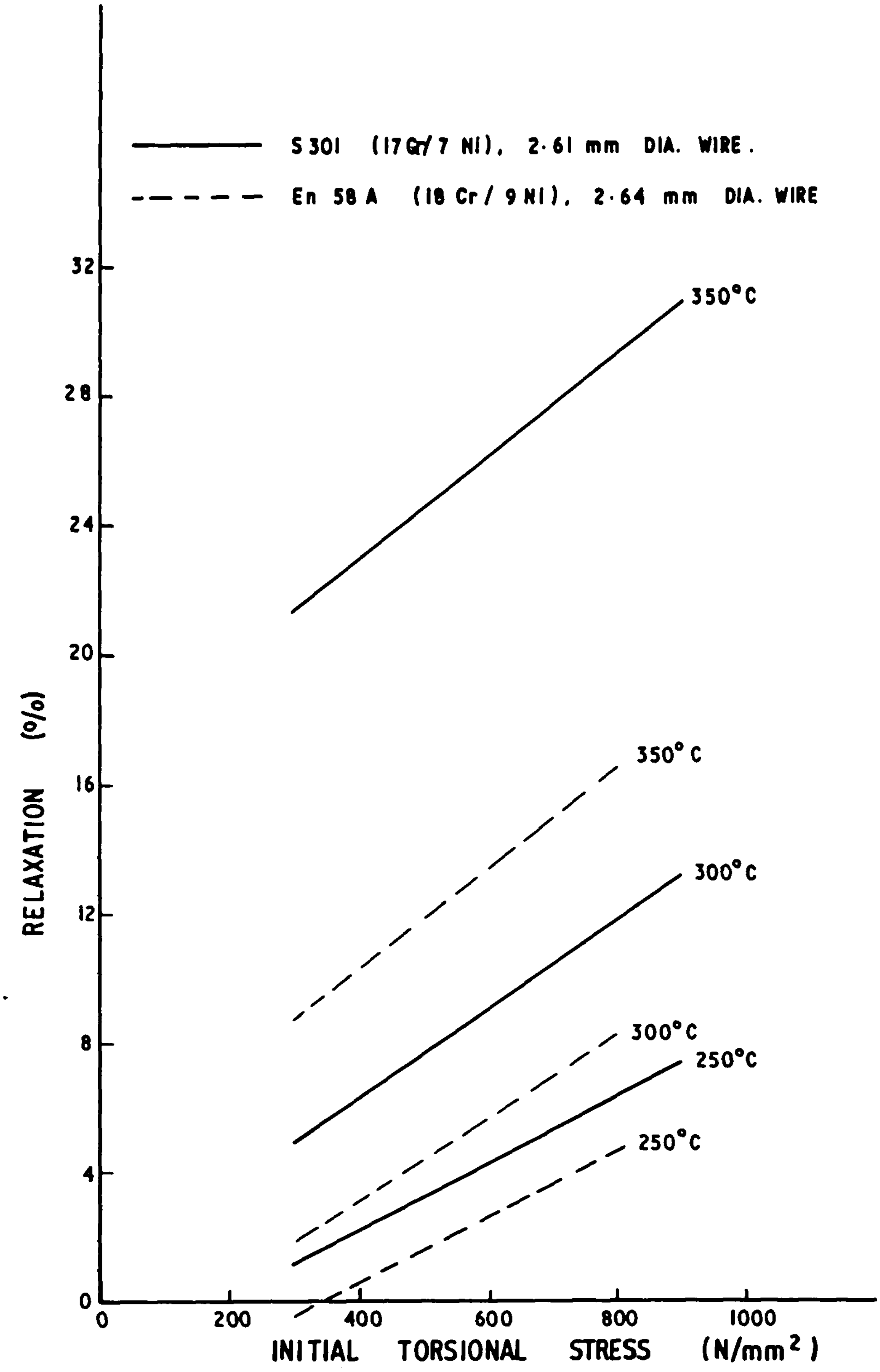

FIG. 19 COMPARATIVE STRESS - RELAXATION CURVES FOR UNPEENED S301 AND EN 58A SPRINGS. (TEST DURATION 168 HOURS.)

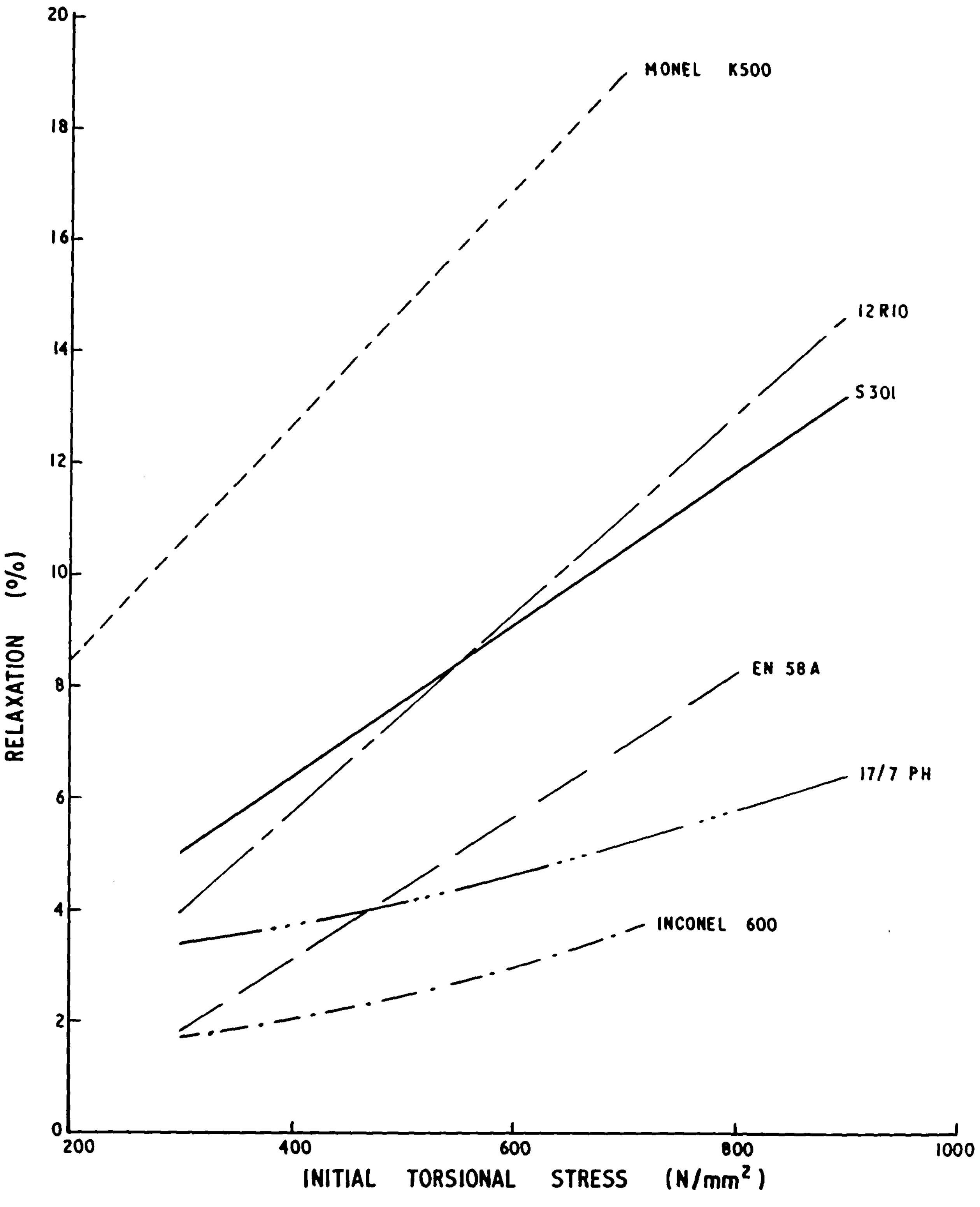

FIG. 20 COMPARATIVE STRESS-RELAXATION CURVES FOR UNPEENED SPRINGS OF VARIOUS MATERIALS. (ALL TESTS AT 300°C)