THE SPRING RESEARCH AND MANUFACTURERS' ASSOCIATION

THE FATIGUE AND RELAXATION OF HIGH STRENGTH TITANIUM 318 ALLOY SPRINGS

by

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

Report No. 288

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SUMMARY AND CONCLUSIONS

Mechanical tests have been carried out on wires of titanium 318 alloy, which were obtained in both the hard drawn and the solution treated and aged conditions. Fatigue tests have also been carried out on springs manufactured from the alloy in both the unpeened and the shot peened conditions.

From the results of these tests, modified Goodman diagrams have been produced which allow the maximum stress to be determined at lives of 10^5 to 10^7 cycles for any level of initial stress.

Dynamic relaxation data after 10^7 cycles have been established for both materials in both the unpeened and the shot peened conditions.

Time-relaxation and stress-relaxation tests were carried out on peened and unpeened springs of both materials.

It was concluded that:

1. The hard drawn alloy possesses the better elastic properties in tension but the torsional properties of both alloys are very similar.

2. The hard drawn alloy possesses the better fatigue properties in the unpeened condition but the performance of both alloys is inferior to that of S205 stainless steel.

3. Shot peening Ti 318 alloy springs produces significant increases in the fatigue strength, ranging from a 50% increase for the hard drawn alloy to over 150% for the solution heat treated and aged alloy.

The fatigue strengths of the alloys after shot peening are consistently greater than those of shot peened springs made from the equivalent Ti 314 alloy.

The fatigue strength, at 10^7 cycles, of the shot-peened, solution heat treated and aged Ti 318 springs is equal to that of unpeened BS 2056.

4. In terms of the fatigue strength/weight ratios, the shot peened Ti 318 alloys are both superior to BS 2056 and BS 5216 springs.

5. The dynamic relaxation properties of the alloys in both the peened and the unpeened condition are good at all stress levels below 85% of the solid stress.

6. All the primary stress-relaxation at 100°C occurs within 72 hours at temperature.

7. The stress-relaxation properties of the solution heat treated and aged Ti 318 springs are superior to those of the hard drawn material, both in the peened and the unpeened conditions.

8. The unpeened, hard drawn Ti 318 springs, in general, exhibit better relaxation characteristics than BS 5216HD (En 49D) springs at temperatures up to 150°C. By contrast, the solution heat treated and aged titanium springs generally exhibit better relaxation properties than the BS 5216HD springs at temperatures above 150°C.

9. The relaxation properties of the shot peened Ti 318 springs are consistently poorer than those of the equivalent Ti 314 alloy springs.

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1. INTRODUCTION

Titanium alloys possess high strength and low density, together with a pronounced resistance to corrosion, the alloys remaining unaffected even in environments containing particularly corrosive compounds, such as strong mineral acids.

Pure titanium can exist in two allotropic forms:

1. alpha (α) phase, which has a close-packed hexagonal (C.P.H.) structure and is stable at temperatures up to 883°C.

2. beta (β) phase, which has a body-centred cubic (B.C.C.) structure, which is stable at temperatures between 883°C and the melting point of the metal.

The addition of 6% aluminium and 4% vanadium converts titanium into an alloy which has a stable structure at room temperature, containing both α and β phases in the annealed condition.

The alloy can be age-hardened after quenching from a solution heat treatment temperature (925°C) at which the structure consists largely of the β phase. (The alloy transforms completely into the β phase at a temperature of 995°C ± 15°C). Upon quenching in water, the B.C.C. β phase transforms, via a diffusionless shear reaction, into a distorted B.C.C. phase which is often termed α martensite, or α'. Subsequent ageing at 480°C causes the α' phase to break down into a very fine dispersion of precipitated B.C.C.β phase in a re-formed C.P.H.α matrix, leading to a substantial increase in strength by a dispersion hardening mechanism.

The annealed α-β alloy can also be strengthened significantly by cold working, with the result that Ti 318 can be used for the manufacture of springs in either the cold worked or the solution heat treated and aged condition.

Previous investigations into the properties of three titanium alloys at the SRAMA[1] established that Ti 318 possessed the best combination of mechanical properties for the manufacture of springs and, in particular, revealed that the fully heat treated alloy showed the most promise in this respect.

Following the recommendations of that report, the present work is intended to provide fatigue and relaxation data on helical compression springs manufactured from Ti 318 wire in both the cold drawn and the fully heat treated conditions. Tests were also undertaken to assess the response of the alloy, in both conditions, to shot peening.

2. MATERIALS

2.1 Composition and Wire Condition

The chemical composition of the material is given in Table. I.

The wire used for this investigation was obtained in two conditions, both having very similar diameters, as follows:

1. cold drawn wire: 30% R. of A. after final annealing, 2.49 mm diameter, supplied in coil form; and

2. fully heat treated and cleaned wire: solution heat treated 925°C/½h; aged 480°C/2h, 2.39 mm diameter, supplied in random lengths.

Macro-examination of the 'as received' wire showed that the cold drawn material was completely satisfactory.

A proportion of the fully heat treated wire, however, showed clear evidence of drawing defects. The whole batch of heat treated wire was therefore subjected to detailed macro-examination, the defective wire being rejected as being unacceptable for spring manufacture.

2.2 Spring Design and Manufacture

Springs were coiled to the designs shown in Table II. The cold drawn material was coiled using an automatic, single-point coiling machine. The heat treated material, however, was hand-coiled by a member firm, since the random lengths supplied were unsuitable for automatic coiling.

All the springs were stress relieved at 250°C/½h after coiling. Half the springs from each batch of material were shot peened, using S230 shot, to an Almen arc rise of 0.38 A2. The peened springs were subsequently stress relieved at 200°C/½h.

3. EXPERIMENTAL PROCEDURE

3.1 Optical Examination

Transverse microsections prepared from the 'as received' material were examined under the optical microscope to assess the surface condition and microstructure of the wire.

3.2 Mechanical Testing

3.2.1 Tensile tests

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, was used in conjunction with the automatic recorder.

3.2.2 Torsion tests

The torsion tests were carried out using a Tinius-Olsen machine, which had a continuously variable angular velocity of 0-180°/min. Although this machine had an automatic torque/angular displacement recorder, appropriate readings were taken manually throughout each test, since the results obtained were then suitable for more precise calculation and interpretation by regression analysis.

The torsional stresses and strain were calculated from the relationships:

$$\tau \text{ (torsional stress)} = \frac{d.T.}{2J} = \frac{16T}{\pi d^3} \qquad \ldots\ldots\ldots\ldots 1$$

and

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

where

d = wire diameter, mm

T = applied torque, N.mm

J = second polar moment of area = $\frac{\pi d^4}{32}$

θ = angular displacement, radians

L = gauge length $\geqslant$100d, mm

3.3 Fatigue Testing

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

Fatigue testing of the unpeened springs was carried out at initial stresses of 100/300 N/mm^2 and 100/200 N/mm^2 for the hard drawn and the heat treated alloys respectively.

All the fatigue tests on shot peened springs were carried out at initial stresses of 50 and 100 N/mm^2.

Each spring was load tested to determine the deflections necessary to give the initial and maximum torsional stresses, the appropriate loads having been calculated from the standard relationship:

$$P = \frac{\pi d^3 \tau}{8DK} \qquad \ldots\ldots\ldots\ldots 3$$

where

P = load, N

τ = shear stress, N/mm^2

D = mean diameter, mm

d = wire diameter, mm

K = Sopwith correction factor = (c + 0.2)/(c-1)

where c = spring index = D/d

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

3.4 Examination of Fractures

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

3.5 Relaxation Tests

3.5.1 General description

Relaxation testing was carried out using a technique which has been described in detail in earlier reports[2,3]. The loads necessary to produce the desired shear stress in the spring were calculated using Equation 3, after which the springs were load tested to obtain the deflections at the calculated loads. Each spring was fitted over a stainless steel bolt and was compressed to the length required for the desired stress by means of a nut, with washers bearing on each ground end of the spring.

An attempt was made to reduce the scatter of the results by coating the ends of the springs with colloidal graphite before assembling the bolts, thus reducing the end restraint resulting from sticking friction between the spring and the restraining washers.

After assembly, the compressed springs were subjected to the selected elevated temperature for the required time, allowed to cool to room temperature, and were then unloaded. The new load at the original compressed length was measured and from the data so obtained, the percentage loss in load was calculated.

All measurements were made at ambient temperature and no allowance was made for the loss in load accompanying the change in rigidity modulus with change in temperature.

If it is required to consider the alteration in stress with temperature, it can be shown that the stress at elevated temperatures can be calculated from the expression:

$$\tau_T = \tau_o \frac{G_T}{G_o} \qquad \ldots\ldots\ldots\ldots\ldots 4$$

where

τ_T = shear stress at temperature, T^oC

τ_o = shear stress at room temperature

G_T = rigidity modulus at temperature, T^oC

G_o = rigidity modulus at room temperature

3.5.2 Time-relaxation tests

Triplicate tests were carried out on springs made from the hard drawn and solution heat treated and aged materials for times of 2, 16, 24, 48, 72 and 100 hours at a temperature of 100^oC, and at initial stresses of 300 and 600 N/mm^2.

3.5.3 Stress-relaxation tests

All these tests were carried out for a time of 72 hours, the time-relaxation tests having confirmed a previous observation that most of the primary relaxation in titanium alloys occurs in this time. The tests were carried out at appropriate stresses within the range 200-600 N/mm^2.

Triplicate tests were carried out on all the hard drawn wire springs. During the course of the work, however, it became clear that the data could be interpreted statistically, since the relaxation invariably proved to vary exponentially with stress.

Subsequent tests on the springs of solution heat treated and aged material were therefore carried out in duplicate, since the analytical relationships derived from the data were sufficiently significant to justify a reduction in the amount of experimental work involved.

4. RESULTS

4.1 Microscopical Examination of Wire

Examination of transverse and longitudinal microsections taken from both the hard drawn and the solution heat treated and aged material showed that both materials possessed a satisfactory surface, with no obvious surface defects.

Microscopical examination after etching in an aqueous solution of 2% HF + 10% HNO_3 revealed the structure of the hard drawn material to consist of highly deformed grains of 'β' in a 'α' matrix.

The structure of the solution heat treated and aged material, by contrast, consisted of primary 'α' grains in an equiaxed matrix of transformed 'α' martensite, in the form of a fine dispersion of 'α' and 'β'. This latter feature, however, is not easily resolved by the optical microscope.

In general, therefore, both materials possessed satisfactory surfaces and showed metallographic structures which were typical of the hard drawn, and the solution heat treated and aged conditions respectively.

4.2 Experimental Results

The chemical compositions of the materials investigated are given in Table I and the spring design data in Table II. The results of the tensile and torsion tests carried out on the wire are given in Tables III and IV respectively.

4.2.1 Fatigue data

Although, in the case of martensitic ferrous materials, a straight line is often used to represent limited data, it is well known that many non-ferrous materials do not show a fatigue limit; hence the fatigue data are better represented by a curve than by a straight line. This proved to be the case in the present instance, for all the results obtained on unpeened material. For all the tests on unpeened material, reciprocal relationships were examined and the relationship giving the best fit was selected to represent the data. The relationships were then transformed back into a log-linear form; these are shown in the form of S/N curves (Figs. 1-4). In all cases, the correlation coefficients obtained were tested to determine whether they were significant at the minimum acceptable level of 95% confidence and this was found to be the case.

In the case of the results obtained with shot peened springs, no failures occurred below 10^6 cycles; hence a linear relationship was used to express the results over the limited range for which data were available.

The fatigue data are shown plotted as S/N curves in Figs. 1-7 and modified Goodman diagrams are presented as Figs. 8-10. The maximum recommended working stresses for the springs (85% of solid stress) are also shown in these ten diagrams.

Fatigue data extracted from the diagrams are shown in Table V, which also shows comparative fatigue data for other spring materials. Dynamic relaxation data are shown in Tables VI and VII.

4.2.2 Relaxation data

The results of the static relaxation tests are shown in Tables VIII - XII and are shown in graphical form in Figs. 11-18.

The time-relaxation appeared to follow a logarithmic relationship, in that most of the primary relaxation occurred early in the test, the rate of change of relaxation with time becoming very low after this primary relaxation had taken place.

The basic data were found to be adequately represented by the relationship:

$$Rel = a \ln t + b \qquad \text{............ 5}$$

where

Rel = % relaxation in time 't' in minutes and 'a' and 'b' are constants

Straight lines of Rel/lnt fitted to this relationship gave correlations which were significant at the 95% level of confidence.

Confidence limits were determined by statistical analysis of the residuals obtained from the relaxation data and the relaxations extracted from the appropriate regression relationship.

The values of the relevant constants, 'a' and 'b', are shown in Table XIII together with the increments for the 95% confidence, which must be added to and subtracted from the calculated values of 'Rel' to give the 95% confidence bands.

The stress-relaxation results, at each of the temperatures at which tests were carried out were found to be adequately described by the exponential relationship:

$$Rel = Ae^{B\tau} - C \qquad \text{............ 6}$$

where

Rel = % relaxation at 72 hours for a given temperature

τ = initial stress

A and B are constants

C = an integer, the value of which was assigned from the results of the work such that $(Rel + C) > 0$. This procedure was necessary for the statistical analysis of the data containing relaxations less than 0% (i.e. recovery), since $\ln 0 = -\infty$.

This type of relationship has been so successfully used to describe the creep behaviour of both metallic and thermoplastic polymer materials[4,5]. It should be noted that the creep behaviour is usually expressed as the creep rate, i.e. $d\varepsilon/dt$. In the present case, the relaxation is analogous to this function, in that it is actually the relaxation at 72 hours.

The exponential relationship can be transformed into a form more suitable for statistical analysis, i.e:

$$\ln(Rel + C) = \ln A + B\tau \qquad \text{............} \quad 7$$

Hence the plot of $\ln(Rel + C)$ against τ should give a straight line, which can be treated by linear regression techniques to give the 50% mean relationship.

All the expressions which were derived to represent the stress-relaxation data gave correlations which were significant at the 99.9% level.

Confidence limits were determined by statistical analysis of the residuals obtained from the stress relaxation data and the relaxations extracted from t he appropriate regression relationship.

The values of the constants, A and B, and for the assigned integer, C, are shown for the various alloys tested in Tables XIV and XV, together with the increments for the 95% confidence limits.

The relaxation curves derived from the analytical expressions are shown in graphical form in Figs 11-18 and relaxation data for comparable spring materials are plotted in Figs 19-21.

The relevant parameters derived from the analytical expressions for stress-relaxation are shown plotted as a function of temperature in Figs 22-29.

Apparent activation energies of relaxation, derived from the variation of relaxation with temperature at constant stress, are shown in Table XVI and the results are plotted as a function of initial stress in Fig 30.

5. DISCUSSION

5.1 Static Mechanical Properties

The results obtained from the tensile and torsion tests were generally satisfactory, although both were somewhat lower than those observed by the Association in previous work on this alloy(1).

The work confirmed the previous observation that low temperature heat treatment of the hard drawn alloy at 250°C/½h resulted in a significant improvement in both the tensile and torsional properties of the material, both these properties showing an increase of 5-10% compared with values obtained in the "as received" hard drawn condition.

The results of the present tests were also similar to those of the previous work, in that the hard drawn alloy tended to possess the best properties in tension, although the torsional properties of the two alloys were very similar.

Although the strengths of the titanium alloys were significantly lower than those obtained for steels, the effects of specific gravity must be considered before a true comparison of the materials can be made.

The comparison can easily be made in terms of the strength to weight ratio, here defined as the ratio of the tensile strength to the specific gravity of the material. The relative cost of the materials is also shown in the table, expressed as a multiple of the cost per kilogram for patented, hard drawn carbon steel wire.

Material	Tensile strength R_m N/mm^2	Specific Gravity	$\frac{R_m}{S.G.}$ N/mm^2	Relative Cost
Ti 318 hard drawn	1350	4.42	305	24
Ti318 solution heat treated and aged	1225	4.42	277	40
S205(6)	1630	8.0	204	2
BS 5216 HD(7)	1825	7.75	235	1

The weight advantage of the titanium alloys can clearly be seen; this is of special significance where the weight of a component is important, such as in the aircraft industry, for example.

In the spring industry, however, the cost of the titanium alloy obviously dictates that the material will only be used when its particular combination of strength, corrosion resistance and surge resistance are of overriding importance. Such conditions may be met, for example, in the context of safety considerations, performance under extreme conditions (as in a highly corrosive, chloride-bearing environment) or of cost-effectiveness, with respect to equipment of high capital investment incurring heavy "downtime" losses and penalties.

5.2 Fatigue Properties

5.2.1 Unpeened springs

The results of the fatigue tests on unpeened springs are shown as Figs 1-4. Whilst the broken springs of the solution heat treated alloy gave a reasonable (reciprocal) correlation, a significant number of springs survived unbroken after 10^7

cycles at relatively high maximum stresses, for both levels of initial stress tested. The curves for this alloy therefore represent the "pessimistic" data for springs which failed before 10^7 cycles. The Goodman diagram (Fig 9) for the unpeened springs of the solution heat treated alloy therefore also represents the "pessimistic" data; consequently this should be interpreted with some caution. Such scatter in fatigue life has often been observed for titanium alloys and confirms the experience of the manufacturer of the wire.

The titanium alloys generally possessed poorer fatigue strengths than either of the stainless and carbon steel alloys shown below for comparison. This is demonstrated most clearly when the fatigue ratios are considered, the ratio here being defined as fatigue strength at zero initial stress/R_m.

Material and Treatment	Life Cycles	Fatigue ratio at zero intial stress
Ti 318 Hard drawn, 2.49 mm dia., L.T.H.T. 250°C/½h	10^6 10^7	0.23 0.16
Ti 318 Solution heat treated and aged, 2.39 mm dia., L.T.H.T. 250°C/½h	10^5 10^6 10^7	0.32 0.20 0.11*
S205 (6) Hard drawn, 1.6 mm dia., L.T.H.T. 450°C/2h	10^7	0.36
BS 5216 HD3 (7) Patented, hard drawn, 2.64 mm dia., L.T.H.T. 350°C/½h	10^6 10^7	0.41 0.39

(*The fatigue ratio at 10^7 for the solution heat treated and aged titanium springs is an extrapolated value and should therefore be treated with some caution).

It can be seen that the values of the ratios for the titanium alloys at 10^7 cycles are considerably lower than the equivalent parameters for either the stainless steel or the carbon steel alloys.

The titanium alloy, however, has a specific gravity of 4.42, compared with the values of 8.0 and 7.75 for the stainless and carbon steels respectively.

If the parameter fatigue ratio at 10^7/specific gravity is considered, the influence of the lower S.G. of titanium becomes clearer.

Material	$\frac{(\text{Fatigue ratio at } 10^7) \times 10^{-2}}{\text{specific gravity}}$
Ti 318 hard drawn	3.6
Ti 318, solution heat treated and aged	2.4
S205	4.5
BS 5216 HD3	5.0

From these data, it can be seen that the hard drawn titanium alloy compares favourably with the stainless steel alloy.

Although the patented, hard drawn carbon steel has the highest ratio, it should be remembered that this alloy offers little protection against the aggressive environments in which the stainless steel or the titanium alloys normally operate; hence, the fatigue strengths are not strictly comparable, unless the carbon steel springs can be adequately protected against the effects of corrosion, pitting attack and embrittlement.

5.2.2 Shot peened springs

The fatigue data for the shot peened springs are shown in graphical form in Figs 5-7, from which it can be seen that a straight line relationship gave the best fit to the results of the work on the hard drawn springs.

The solution heat treated springs, by comparison, remained unbroken after 10^7 cycles at all stress levels; it can therefore be stated only that the material had a fatigue strength, at 10^7 cycles, in excess of the highest stress level tested.

The data presented in Table IV show that shot peening dramatically increased the fatigue strength of both the hard drawn and the solution heat treated alloy springs.

The effects of shot peening on the fatigue strength at 10^7 cycles and at an initial stress of 100 N/mm^2 are shown below, together with comparable data for other spring materials. (Details of the relevant low temperature heat treatment can be found in Table V).

Material	Fatigue strength at 10^7 cycles N/mm^2		Percentage increase in fatigue strength
	Unpeened	Peened	
Ti 318 hard drawn	325	530	63
Ti 318 solution heat treated and aged	230*	>600	∿160
Ti 314A[8] hard drawn	-	400**	-
Ti 314A[8] solution heat treated and aged	-	540**	-
BS 2056[9] (En 58A)	600	820	37
BS 5216 HD3[7]	785	925	18

* Extrapolated value ** Initial stress of 80 N/mm^2

The value of the fatigue strength for the unpeened solution heat treated Ti 318 alloy has been obtained by extrapolation of the appropriate regression relationship to 10^7 cycles; this value should therefore be treated with some caution. Nevertheless, the data serve to indicate the pronounced response to shot peening of the titanium alloys, as compared with that of the other two ferrous alloys shown.

It is also apparent, from the data given, that the fatigue strength of the Ti 318 alloys in the shot peened condition is greater than that for the equivalent Ti 314 alloy.

Furthermore, for both Ti 318 and Ti 314, the fatigue strength of the solution treated and aged alloy, after shot peening, is greater than that of the hard drawn alloy.

If the specific gravity of the alloys is considered, the relative effects of shot peening upon the fatigue ratio at zero initial stress of both the titanium alloy and the ferrous alloy with the highest fatigue strength after shot peening can clearly be seen.

Material	(Fatigue ratio at 10^7/S.G.) x 10^{-2}	
	Unpeened	Shot peened
Ti 318 hard drawn	3.6	8.4
Ti 318, solution treated and aged	4.5	11.1
BS 5216 HD3	5.0	5.9

In general terms, the pronounced effect of shot peening upon the fatigue properties of the polycrystalline titanium alloy may be partly attributed to the fact that close packed hexagonal metals, such as titanium, work-harden about 4 times faster than face-centred cubic metals, such as austenitic stainless steels or nickel alloys, thus leading to a greater strengthening effect at the surface of the wire.

From these data it would therefore appear that, weight for weight, the fatigue strength of the titanium alloy springs is greater than that of equivalent springs made from a high strength carbon steel alloy: shot peened titanium alloys thus have particular advantages where both weight and corrosion resistance are of primary importance. It is of further interest that the fatigue strength of the solution heat treated and aged Ti 318 in the shot peened condition is equal to that of unpeened BS 2056 stainless steel. The titanium alloy springs may therefore prove useful in environments which are potentially aggressive towards the stainless alloys, such as atmospheres or solutions having high chloride contents.

The effect of low specific gravity upon the dynamic performance of the titanium alloys is also important with respect to the accompanying low inertia of the alloys, which results in a higher natural frequency, with a concomitant decrease in the occurrence of surging at high speeds. This is significant in that resonant oscillation of a spring at its natural frequency, or at some higher harmonic of this, may lead to the generation of high stresses, with the possibility of premature failure of the component.

5.3 Dynamic Relaxation after 10^7 Cycles

The dynamic relaxation of the hard drawn springs was generally less than 2%, with a maximum value of 3% for the peened springs tested over the greatest stress range.

The unpeened springs of the solution heat treated alloy also showed good dynamic relaxation properties, some springs apparently giving a slight indication of recovery during testing. These latter results appeared to be distributed at random throughout the stress levels investigated, no clear-cut pattern of occurrence being apparent.

The peened springs of solution heat treated Ti 318 generally exhibited low values of dynamic relaxation, of the order of 1-2%, except at combinations of low initial stress and high maximum stresses (close to solid), where the relaxation was about 5-6%.

5.4 Examination of Fatigue Fractures

The fracture surfaces of all the broken springs were very similar in appearance, irrespective of wire condition, spring condition, or the initial and maximum stresses employed during the test.

Fracture invariably initiated on the inside of the coil, at the most highly stressed region of the wire. This was generally true of both the peened and unpeened springs, although the initiation of the former tended to be sub-surface in origin. It is known that titanium alloys exhibit poor surface properties in rubbing friction, because of the ease with which galling and seizing can occur; particular attention should therefore be paid to the lubrication of the wire during coiling.

After initiation, the fatigue crack progressed in transverse shear for a short distance, after which further crack growth was in the 45° tensile helicoidal mode, this latter portion comprising the larger part of the fracture. Final fracture was invariably in transverse shear, although small regions of longitudinal shear were also occasionally present in this final fracture zone.

5.5 Static Relaxation Properties

5.5.1 Time-relaxation of peened and unpeened springs

The time-relaxation plots revealed that, for all the materials, in both the peened and the unpeened conditions, over 94% of the relaxation occurring in 100 hours had taken place in 72 hours. This confirmed the propriety of testing the springs under stress relaxation conditions for 72 hours, almost all of the primary relaxation having occurred within this time.

5.5.2 Stress-relaxation of unpeened springs

Examination of the relaxation behaviour, depicted in Figs 15-16, shows that the hard drawn material possessed the best relaxation resistance at temperatures less than 100°C at all of the stress levels investigated, and especially at initial stresses of less than 300 N/mm^2, where a small amount of recovery was observed.

The solution heat treated and aged material showed the best relaxation properties at a temperature of 200°C. At a temperature of 150°C, however, the relaxation properties of both alloys were virtually identical over the complete range of initial stresses investigated.

These observations, which result from consideration of the appropriate curves, probably constitute a reasonable assessment of the relative stress-relaxation behaviour of the alloys at equivalent temperatures and stresses.

It should be pointed out, however, that statistical analysis of the basic data suggests that no difference exists, at the 5% level of significance, between the stress-relaxation behaviour of springs manufactured from the alloy in the hard drawn and in the solution heat treated and aged conditions at equivalent temperatures.

Comparison of the data with those available for BS 5216HD (EN 49D) carbon steel and 18/8 stainless steel alloys, plotted in Fig 19 from previous work at the Association[2,10], reveals that the stainless alloy showed the best relaxation behaviour of all the materials considered at 150°C.

The hard drawn titanium alloy springs were superior to the carbon steel springs at temperatures and initial stresses of less than 150°C and 400 N/mm^2 respectively, but showed greater relaxation values than the carbon steel at a temperature of 200°C.

The solution heat treated and aged titanium alloy springs, however, showed lower relaxation values than the carbon steel at temperatures above 150°C and at initial stresses less than 500 N/mm^2. The carbon steel springs, however, were superior at temperatures less than 100°C at all the initial stress levels investigated.

5.5.3 Stress-Relaxation of shot peened springs

The stress-relaxation properties of the shot peened alloys appeared to be consistently inferior to those of the unpeened springs. The difference tended to be less marked for the solution heat treated and aged alloys, however, although there was no statistically significant difference at the 5% level, for either of the alloys over the temperature range investigated.

The relaxation properties of the solution heat treated and aged titanium alloy springs appeared to be consistently better than those of equivalent hard drawn material at all the temperatures investigated, the difference in properties becoming more pronounced at temperatures exceeding 150°C. Once again, however, there was no difference in the relaxation behaviour of the shot peened springs at the 5% level of significance for either of the two alloys considered.

Comparison of the results for springs in the shot peened condition with the data from the previous work at the SRAMA on Ti 314A alloy springs[8], as shown in Figs 20 and 21, reveals that the Ti 314A alloy consistently exhibited better relaxation behaviour than the equivalent Ti 318 alloy springs at temperatures of 100°C and 150°C. This finding may require further investigation, in view of the fact that the Ti 318 alloy is generally considered to exhibit better creep properties than Ti 314A at temperatures in excess of 300°C. It must be remembered, however, that superior creep properties at a low temperature are not always accompanied by equivalent performance at higher temperatures.

5.5.4 Temperature interpolation for stress-relaxation

It has been stated previously that the stress-relaxation at a particular temperature was found to vary exponentially with stress (Equation 6).

From Tables XIV and XV, it can be seen that the constants 'A' and 'B' appear to vary systematically with temperature. This suggests that it may be possible to express both constants as functions of temperature, f(T), i.e:

$$A = f_1 (T)$$

and $$B = f_2 (T)$$

The expression for relaxation would then be of the general form:

$$Rel = f_1 (T) e^{f_2 (T) \tau}$$

This would lead to a general expression for the amount of relaxation over the whole range of temperatures and initial stresses investigated.

In view of the limited number of temperatures employed in the present investigation, it was not always possible to derive an analytical expression which adequately represented the appropriate functions of temperature for the terms 'A' and 'B'.

As a result, it was felt that a graphical interpolation, would be the only suitable method of presentation in this instance. Diagrams relating both the parameters 'A' and 'B' to temperature are shown for the relevant alloys in Figs 22-29.

It is extremely interesting to note that the graphs for the appropriate constant are very similar in form indicating that both constants do vary with temperature in a systematic manner.

The values of the constants 'A' and 'B', which are appropriate to a particular alloy for temperatures between 75°C and 200°C, can be obtained from the graphs, after which the percentage relaxation can be calculated from the appropriate relationship of the form:

$$\text{Rel} = Ae^{B\tau} - C$$

(The assigned integer 'C' will only be >0 when some recovery is present.)

It must be emphasised that the interpolation is necessarily approximate at present, owing to the paucity of data available, and the results obtained should therefore be treated with caution. Nevertheless, the use of this technique should allow the relaxation to be calculated to within $\pm 1\%$ absolute relaxation (i.e. $n \pm 1)\%$.

Further work would lead to more definitive expressions for the appropriate temperature functions, resulting in an improved interpolation technique.

5.6 Apparent Activation Energies for Stress Relaxation

Examination of the relaxation data, at constant stress, as a function of temperature showed that the temperature-relaxation behaviour was well represented by an expression of the form:

$$\text{Relaxation }\%/72\text{ hours} = De^{-F/T} \qquad \ldots\ldots\ldots\ldots\ 8$$

where

T = relaxation temperature, $^{\circ}$K (absolute)

D and F = constants, which vary with the initial stress level of the test

This can therefore be expressed in the form of a linear relationship:

$$\ln(\text{Rel}) = \ln D - F\left(\frac{1}{T}\right) \qquad \ldots\ldots\ldots\ldots\ 9$$

where

-F is the slope of the straight line obtained by plotting lm(Rel) against $(\frac{1}{T})$

and lnD = constant of proportionality

Regression analyses carried out on the appropriate data gave correlations which were significant at the 99% level of the 't' distribution in every case but one, the odd case being attributed to the limited data available for the analysis.

The apparent activation energy for the physical processes leading to a reduction in the strain energy of the stressed material (i.e. relaxation) can be calculated from the slope of the regression curve, since:

$$F = \frac{Q}{R}$$

where

Q = apparent thermal activation energy, Joules/mol

and R = gas constant, = 8.36 J/mol/$^{\circ}$K

(1 electron volt (eV) = 96,300 J/mol)

Hence it may be said that:

$$\text{relaxation \%/72 hours} = De^{-\frac{Q}{RT}} \qquad \text{............ 10}$$

This expression of relaxation rate, once again is very similar to those determined for the variation in creep rate, $d\varepsilon/dt$, with temperature in both metals and thermoplastics[4,5].

Values of the activation energies for the two alloys in both the peened and unpeened conditions are given in Table XVI and are shown plotted against initial stress in Fig 30.

It can be seen from this curve that the apparent thermal activation energy decreases as the initial stress increases. This can be undersood if both the initial stress and the thermal activation energy are considered to contribute to the total amount of energy necessary for the processes governing relaxation to occur, i.e:

$$E_T = I + Q + \tau \qquad \text{............ 11}$$

where

E_T = total energy required for relaxation to occur
I = internal strain energy contribution, in the form of line and lattice defects, dislocations, vacancies, etc.
Q = apparent thermal activation energy
τ = externally applied strain energy, in the form of the applied initial stress

If both E_T and the internal strain energy contribution, I, for relaxation are considered to be approximately constant for an alloy in a given condition, then it can readily be seen that the thermal activation energy and the applied initial stress will vary inversely with each other, as shown in Fig 30.

By the same reasoning, the displacement of the apparent activation energy for the hard drawn material to lower values upon shot peening can be explained in terms of an increase in the internal strain energy contribution, I, resulting from the plastic deformation at the surface of the wire which results from shot peening. If E_T remains constant, then an increase in I should result in a concomitant decrease in the $(Q + \tau)$ components of E_T.

By contrast, however, the apparent thermal activation energy of the solution heat treated material increased upon shot peening. This behaviour was consistent at all the stress levels investigated but is not yet fully understood, and may require further investigation if a clearer understanding of this aspect of the behaviour of the titanium alloy is considered desirable.

The apparent thermal activation energies for these materials generally fell within the range 0.1 - 0.5 eV. It is interesting to note that these values lay within the range obtained for transient, and the lower range of steady state, creep (secondary) in those face centered cubic metals with which titanium has certain similarities.

These levels of activation energy (e.g. of 0.25-0.75 eV for aluminium, for example) are generally considered to be associated with a combination of pure dislocation glide, and thermally activated cross-slip of locked dislocations, which are circumventing obstacles opposing their movement through the structure[11].

6. CONCLUSIONS

1. The hard drawn titanium alloy possesses the best elastic properties in tension. The torsional properties of the hard drawn and the solution heat treated material are very similar, however.

2. The hard drawn titanium alloy springs possess the best fatigue properties in the unpeened condition.

   The fatigue strength in the unpeened condition is lower than that for either S205 stainless steel or BS 5216 HD3 carbon steel springs.

3. When the specific gravity of the alloys is considered, the fatigue strength/weight ratio of the hard drawn

unpeened alloy springs compares favourably to that of unpeened stainless steel springs.

4. Shot peening produces very significant increases in the fatigue strength of the titanium alloys, ranging from over 60% for the hard drawn alloy to an estimated 160% for the solution heat treated material. The strengths in the shot peened condition are consistently greater than those of the equivalent Ti 314A springs.

5. The strength at 10^7 cycles, after shot peening, of the solution heat treated alloy is approximately equal to that of unpeened BS 2056 springs.

6. When the specific gravity of the alloys is taken into consideration, the peened titanium alloys investigated show fatigue strength/weight ratios which are superior to those of either the BS 2056 or the BS 5216 peened springs.

7. The dynamic relaxation properties after 10^7 cycles at room temperature are generally good, being less than 3% for all conditions other than low initial stress and high maximum stresses which are close to the solid stress, i.e. at maximum stresses up to 85% of the solid stress.

8. The time-relaxation investigations have confirmed the propriety of carrying out the stress relaxation tests for a time of 72 hours.

9. Statistical analysis of the stress-relaxation data has shown that there is no significant difference at the 5% level in the stress-relaxation behaviour at equivalent temperatures of springs made from the two forms of Ti 318 alloy in either the peened or the unpeened condition.

10. The form of the relevant curves, however, suggests that springs made from both of the unpeened alloys show very similar stress-relaxation properties at 150°C. The solution heat treated springs tend to be consistently better above this temperature, whilst the hard drawn alloy

appears to be superior at lower temperatures. The relaxation properties of the hard drawn titanium alloy springs are generally superior to those of BS 5216HD (En 49D) at temperatures less than 150°C. By contrast, the solution heat treated and aged titanium alloy springs show better relaxation properties than the BS 5216HD springs at temperatures above 150°C, the steel springs being generally superior at the lower temperatures.

11. The stress-relaxation of the shot peened springs appears to be consistently greater than that of the unpeened springs, as represented by the appropriate curves, even though no statistical difference at the 5% level of significance is apparent from consideration of the basic data.

The solution heat treated and aged springs show the best stress relaxation properties after shot peening.

12. The stress-relaxation properties of the two shot peened alloys are consistently poorer than those of the equivalent Ti 314A alloys.

13. It has been demonstrated that, at constant temperature, the relaxation in 72 hours varies exponentially with the initial stress.

14. The work has shown that the relaxation at constant initial stress is an exponential function of the reciprocal of the absolute temperature.

The apparent activation energy for relaxation has been derived for both alloys, and a qualitative explanation for its variation with initial stress has been suggested.

15. It has been shown that interpolation in graphical form for the stress relaxation at varying temperatures can be achieved.

7. RECOMMENDATIONS

1. Further work is required to explain the scatter of the fatigue data obtained for unpeened springs of the solution heat treated alloy.

2. The low temperature heat treatment given to the alloys after shot peening requires optimisation. It is possible that a considerable increase in relaxation resistance could be obtained with little decrease in the fatigue strength of shot peened springs.

3. It is possible that the analytical approach to the relaxation properties adopted in this work may be applicable to other materials and conditions.

8. REFERENCES

1. Haynes, R., and Mee, J.W., The mechanical properties of 314A, 317 and 318A titanium alloy wires. SRAMA Report No. 112.

2. Graves, G.B., The stress-temperature relaxation properties of springs made from oil-tempered and patented hard drawn wires. C.S.F.R.O. Report No. 115.

3. Graves, G.B., The stress-temperature relaxation and creep properties of some spring materials. SRAMA Report No. 143

4. Mclean, D., and Hale, K.F., The stress-sensitivity of creep. Iron and Steel Institute Special Report No. 70. Structural processes in creep. p. 19 (paper) and p. 90 (discussion).

5. Ellis, B., The structure and properties of thermoplastics. The Metallurgist and Materials Technologist, 1976, (3), March, p. 150.

6. Gray, S.D., The fatigue and associated mechanical properties of helical compression springs manufactured from S205 spring wire. SRAMA Report No. 206.

7. Brummitt, K., The fatigue properties of springs manufactured from material to BS 5216. SRAMA Report No. 277

8. Graves, G.B., and Mee, J.W., Titanium 314A wire and springs (Part 1). SRAMA Report No. 149.

9. Bird, G.C., Shot peening and the effect of shot size on spring performance. SRAMA Report No. 267.

10. Gross, S.C., and Graves, G.B., Titanium 314A wires and springs (Part 2). SRAMA Report No. 149.

11. Friedel, J., Dislocations. International Series of Monographs on solid state physics, 3, 1964 (Pergamon Press).

TABLE I CHEMICAL COMPOSITION OF TITANIUM 318

Element %	Cast Number*	
	JD6280	BB5442
Aluminium	5.50	5.65
Vanadium	4.35	4.20
Iron	0.15	0.15
Hydrogen	0.012	0.0065
Titanium	remainder	remainder

* Hard drawn material manufactured from both casts, solution treated and aged material made from cast JD6280 only.

TABLE II SPRING DESIGN AND HEAT TREATMENT

Design parameters	Hard drawn	Solution heat treated and aged
Wire diameter, mm	2.49	2.39
Mean coil diameter, mm	19.48	19.58
Total coils	5.5	5.5
Active coils	3.5	3.5
Solid stress, N/mm^2 (calculated from load tests)	650-700	640-680
Heat treatment	Hard drawn, coiled, LTHT 250°C/½ h	S.T. 925°C/½ h aged 480°C/2 h coiled, LTHT 250°C/½ h

TABLE III TENSILE TESTS ON TITANIUM 318 WIRE

Material Condition	Tensile Results					
	R_m N/mm^2	L.of P. N/mm^2	$R_{p0.1}$ N/mm^2	$R_{p0.2}$ N/mm^2	R.of A. %	Elong. %
Hard drawn**	1330	570	1040	1190	37	N.D.
Hard drawn and LTHT (2)*	1350	630	1100	-	33	2
Solution treated and aged (2)*	1220	610	1080	1140	47	8

TABLE IV TORSION TESTS ON TITANIUM 318 WIRE

Material Condition	Torsion Results			
	L.of P. N/mm^2	0.1% P.S. N/mm^2	0.2% P.S. N/mm^2	G N/mm^2
Hard drawn (3)*	450	560	610	3.7×10^4
Hard drawn and LTHT (3)*	470	600	650	3.9×10^4
Solution treated and aged (3)*	470	620	660	4.0×10^4

* Figures in parantheses refer to number of samples tested

** Results of one test only, all remainder having broken in grips

TABLE V FATIGUE DATA FOR SHOT PEENED SPRINGS OF TITANIUM 318 AND COMPARABLE SPRING MATERIALS

Material	Material condition	R_m N/mm^2	Life N cycles	Fatigue strength at initial stress, N/mm^2		Fatigue ratio at zero I.S.
				0	100	
Ti 318[a]	Cold drawn 2.49 mm dia LTHT 250°C/½h	1350	10^7	500	530	0.37
Ti 318[a]	Solution treated and aged, 2.39 mm dia LTHT 250°C/½h	1220	10^7	-	>600	-
Ti 314[b]	Hard drawn, 3.25 mm dia LTHT 200°C/½h (Ref. 8)	1340	10^7	-	400*	-
Ti 314[b]	Solution treated and aged, 500°C/2h (Ref. 8)	1260	10^7	-	540*	-
BS 2056[c] (En 58A)	Hard drawn, 1.22 mm dia LTHT 450°C/2h (Ref. 9)	-	10^7	-	820	- -
BS 5216[d]	Patented, hard drawn, 2.64 mm dia LTHT 350°C/½h	1825	10^7	840	925	0.46

*Initial stress 80 N/mm^2 (5 tonf/in^2)
(a) shot peened 0.38 A2; stress relieved 200°C/½h
(b) shot peened 0.46 - 0.51 A2; stress relieved 200°C/½h
(c) shot peened 0.28 - 0.30 A2; stress relieved 220°C/½h
(d) Shot peened 0.38 A2; stress relieved 225°C/½h

TABLE VI DYNAMIC RELAXATION OF UNPEENED SPRINGS MADE FROM TITANIUM 318 WIRE

Material condition	Initial stress, N/mm^2	Maximum stress, N/mm^2	Life, N cycles	Dynamic relaxation %
Hard drawn	100	330	1.45×10^7	1.3
	"	295	1.45×10^7	0.6
	300	575	3.0×10^7	0.6
	"	525	3.0×10^7	1.0
	"	520	2.7×10^7	1.3
Solution treated and aged	100	470	1.21×10^7	1.2
	"	470	1.02×10^7	0
	"	405	1.04×10^7	-0.5
	"	400	1.02×10^7	-1.4
	"	380	1.02×10^7	1.0
	"	375	1.02×10^7	-1.0
	"	330	1.04×10^7	0.6
	"	305	1.04×10^7	0
	"	275	1.04×10^7	-0.7
	200	535	1.12×10^7	0.7
	"	510	1.05×10^7	0.4
	"	490	1.02×10^7	-0.8
	"	480	1.02×10^7	0.4
	"	460	1.21×10^7	-0.8
	"	420	1.04×10^7	0.5
	"	400	1.04×10^7	0.5
	"	380	1.04×10^7	0

TABLE VII DYNAMIC RELAXATION OF SHOT PEENED SPRINGS MADE FROM TITANIUM 318 WIRE

Material condition	Initial stress, N/mm^2	Maximum stress, N/mm^2	Life, N cycles	Dynamic relaxation %
Hard drawn	50	575	1.04×10^7	2.6
	"	535	1.02×10^7	2.2
	100	505	1.11×10^7	0
	"	490	1.11×10^7	-0.7
Solution heat treated and aged	50	605	1.48×10^7	5.8
	"	535	1.02×10^7	1.1
	"	520	1.6×10^7	0.4
	"	520	1.02×10^7	0.8
	"	495	1.22×10^7	5.6
	"	455	1.25×10^7	0
	100	600	1.42×10^7	2.0
	"	580	1.06×10^7	2.4
	"	535	1.28×10^7	0.4
	"	520	1.24×10^7	2.6

All springs shot peened 0.38A2; stress relieved 200°C/½h

TABLE VIII TIME-RELAXATION RESULTS AT 100°C FOR TITANIUM 318 SPRINGS

Relaxation Time, h	% Relaxation for material and stress, N/mm²							
	Hard drawn		Hard drawn, S/P*		S.T. and aged		S.T. and aged, S/P*	
	300	600	300	600	300	600	300	600
2	0.3	9.2	1.7	7.3	1.2	9.9	1.0	8.0
"	0	6.2	0.8	8.1	0.6	7.3	0.8	9.2
"	0	5.9	1.1	9.0	0.8	7.3	0.8	8.7
16	0.8	6.4	1.1	8.7	1.0	10.0	1.9	10.1
"	0.6	7.8	1.3	9.0	1.2	9.6	1.2	11.3
"	1.7	9.2	2.3	8.7	0.8	11.7	1.2	8.1
24	2.0	7.7	2.5	8.3	0.4	9.0	1.2	12.7
"	1.7	7.1	2.5	6.4	1.6	10.3	1.5	10.4
"	1.7	8.1	2.3	10.4	0.8	10.5	1.2	11.4
48	0	6.9	1.7	9.2	0.8	9.4	1.2	10.7
"	0.8	7.6	3.4	11.6	0.8	9.8	2.1	11.9
"	0.8	7.3	2.8	10.4	1.0	11.8	1.2	11.3
72	-0.6	8.8	1.1	11.5	1.6	10.4	1.7	8.5
"	0	7.4	1.4	10.1	1.6	11.8	1.6	9.9
"	0.3	7.6	1.7	10.5	-	-	-	-
100	1.1	9.2	1.7	10.9	1.2	11.0	1.6	13.8
"	1.1	6.2	1.7	8.8	1.2	11.2	2.5	12.1
"	2.3	9.0	3.4	10.4	1.6	9.9	2.9	13.7

*Shot peened 0.38A2; stress relieved 200°/½h

TABLE IX STRESS-RELAXATION RESULTS FOR UNPEENED SPRINGS MANUFACTURED FROM HARD DRAWN TITANIUM 318 WIRE

Initial stress, N/mm2	% Relaxation after 72 h at temperature (°C)			
	75	100	150	200
200	-1.7	-0.8	2.1	6.7
"	0.4	-0.8	2.1	6.7
"	0	0	2.1	-
300	-0.6	-0.6	2.3	7.9
"	-0.6	0	1.7	7.3
"	0.6	0.3	2.3	7.9
400	0.8	0.4	4.6	9.7
"	1.3	1.5	4.2	9.7
"	0.6	1.5	4.4	9.7
500	2.5	3.0	8.3	13.5
"	2.7	3.4	7.9	14.8
"	2.5	4.2	7.2	15.5
600	6.2	8.8	13.3	17.8
"	5.9	7.4	10.6	17.8
"	5.9	7.6	11.5	17.4

TABLE X STRESS-RELAXATION RESULTS FOR UNPEENED SPRINGS MANUFACTURED FROM SOLUTION HEAT TREATED AND AGED TITANIUM 318 WIRE

Initial stress, N/mm^2	% Relaxation after 72 h at temperature (^oC)				
	75	100	150	175	200
200	1.2	3.0	1.1	2.5	3.0
"	1.2	3.0	-	1.8	3.7
250	-	-	1.4	-	-
300	1.2	1.6	1.3	2.9	4.9
"	1.2	1.6	-	2.9	4.3
350	-	-	2.4	-	-
400	2.5	2.8	2.6	4.9	6.8
"	3.0	3.4	-	4.9	7.6
450	-	-	3.4	-	-
500	4.9	5.4	7.2	7.5	11.6
"	3.9	4.1	-	7.6	12.7
550	-	-	8.7	-	-
600	8.0	10.4	12.4	12.5	16.5
"	7.6	11.8	-	12.7	17.2

TABLE XI STRESS-RELAXATION RESULTS FOR SHOT PEENED SPRINGS MANUFACTURED FROM HARD DRAWN TITANIUM 318 WIRE

Initial stress, N/mm^2	% Relaxation after 72 h at temperature (^{o}C)			
	75	100	150	200
200	1.3	1.7	3.8	10.1
"	1.7	1.3	3.4	10.9
"	0.8	0.8	4.2	9.7
300	2.0	1.1	4.5	11.2
"	1.7	1.4	4.5	11.8
"	1.7	1.7	5.3	10.1
400	1.7	2.9	7.4	14.5
"	2.1	2.7	7.6	13.0
"	3.4	3.8	7.6	13.5
500	5.6	6.4	10.8	17.0
"	5.2	6.7	10.8	16.2
"	5.1	7.4	11.1	17.2
600	9.9	11.5	13.9	20.2
"	7.7	10.1	15.0	18.8
"	8.5	10.5	14.6	20.2

All springs shot peened 0.38A2; stress relieved $200^{o}C/\frac{1}{2}h$.

TABLE XII STRESS-RELAXATION RESULTS FOR SHOT PEENED SPRINGS MANUFACTURED FROM SOLUTION HEAT TREATED AND AGED TITANIUM 318 WIRE

Initial stress, N/mm2	% Relaxation after 72 h at temperature (°C)				
	75	100	150	175	200
200	0	0.6	2.0	3.7	5.6
"	0.3	0.6	-	3.7	5.9
250	-	-	3.8	-	-
300	1.7	1.7	4.7	4.9	7.3
"	1.2	1.6	-	4.9	6.6
350	-	-	4.5	-	-
400	1.9	2.5	4.5	7.7	9.5
"	2.2	3.7	-	7.7	10.2
450	-	-	4.0	-	-
500	4.6	5.7	8.3	12.5	10.8
"	5.6	6.2	-	10.6	13.8
550	-	-	12.0	-	-
600	8.0	8.5	12.7	15.4	17.5
"	8.3	9.9	-	14.0	19.8

All springs shot peened 0.38A2; stress relieved 200°C/½h.

TABLE XIII ANALYTICAL CONSTANTS FOR LOGARITHMIC TIME-RELAXATION OF PEENED AND UNPEENED TITANIUM 318 SPRINGS, RELAXATION CONDITIONS: 100°C/72 H

Material condition	Spring condition	Initial stress, N/mm^2	Constants for Rel = a lnt + b		Increment for 95% confidence = $\pm$ 1.96 x S_R**
			a	b	
Hard drawn	U/P	300	0.346	-1.383	1.0
	U/P	600	0.608	3.015	1.3
	S/P*	300	0.355	-0.597	1.3
	S/P*	600	0.642	4.690	2.1
Solution treated and aged	U/P	300	0.183	-0.213	0.6
	U/P	600	0.655	5.294	1.9
	S/P*	300	0.293	-0.615	0.8
	S/P*	600	1.077	3.421	1.6

* Shot peened 0.38A2; stress relieved 200°C/½h

TABLE XIV ANALYTICAL CONSTANTS FOR EXPONENTIAL STRESS-RELAXATION OF UNPEENED TITANIUM 318 SPRINGS

Material condition	Temp. °C	Constants for Rel = $(Ae^{B\tau}) - C$			Increment for 95% confidence = $\pm$ 1.96 x S_R**
		A	$Bx10^{-3}$	C	
Hard drawn	75	0.424	4.824	2	1.1
	100	0.455	5.009	2	1.2
	150	1.812	3.302	2	1.6
	200	5.180	2.213	2	1.6
Solution treated and aged	75	0.365	4.989	0	0.9
	100	0.250	6.172	0	1.6
	150	0.256	6.305	0	1.4
	175	0.697	4.794	0	0.3
	200	1.380	4.204	0	1.2

**S_R = Standard deviation of the Residuals derived from the difference between the experimental stress-relaxation data and the values obtained from the analytical expression.

TABLE XV ANALYTICAL CONSTANTS FOR EXPONENTIAL STRESS-RELAXATION OF SHOT PEENEDTITANIUM 318 SPRINGS

Material condition	Temp. °C	Constants for Rel = $(Ae^{B\tau}) - C$			Increment for 95% confidence ≐ ± 1.96 x S_R**
		A	Bx10^{-3}	C	
Hard drawn	75	0.396	5.024	0	1.4
	100	0.304	5.948	0	1.3
	150	1.793	3.52	0	0.9
	200	6.917	1.733	0	1.4
Solution treated and aged	75	0.114	7.335	0	1.5
	100	0.193	6.679	0	1.7
	150	1.106	3.945	0	2.7
	175	1.769	3.610	0	1.5
	200	3.107	2.933	0	2.3

All springs shot peened 0.38A2; stress relieved 200°C/½h

TABLE XVI APPARENT ACTIVATION ENERGIES OF STRESS-RELAXATION (ELECTRON VOLT, eV)* FOR SPRINGS MANUFACTURED FROM TITANIUM 318 WIRE

Material condition	Spring condition	Apparent Activation Energy (eV) for Initial Stress (N/mm²)				
		200	300	400	500	600
Hard drawn and L.T.H.T.	U/P	-	-0.50	-0.30	-0.20	-0.12
	S/P+	-0.26	-0.23	-0.21	-0.13	-0.09
Solution treated and aged	U/P	-0.1	-0.13	-0.10	-0.11	-0.08
	S/P+	-0.34	-0.19	-0.18	-0.11	-0.09

*1 eV = 96,300 Joules/mol = 23 Kcal/mol.

+Springs shot peened 0.38A2; stress relieved 200°C/½ h.

**S_R = Standard deviation of the Residuals derived from the difference between the experimental stress-relaxation data and the values obtained from the analytical expression.

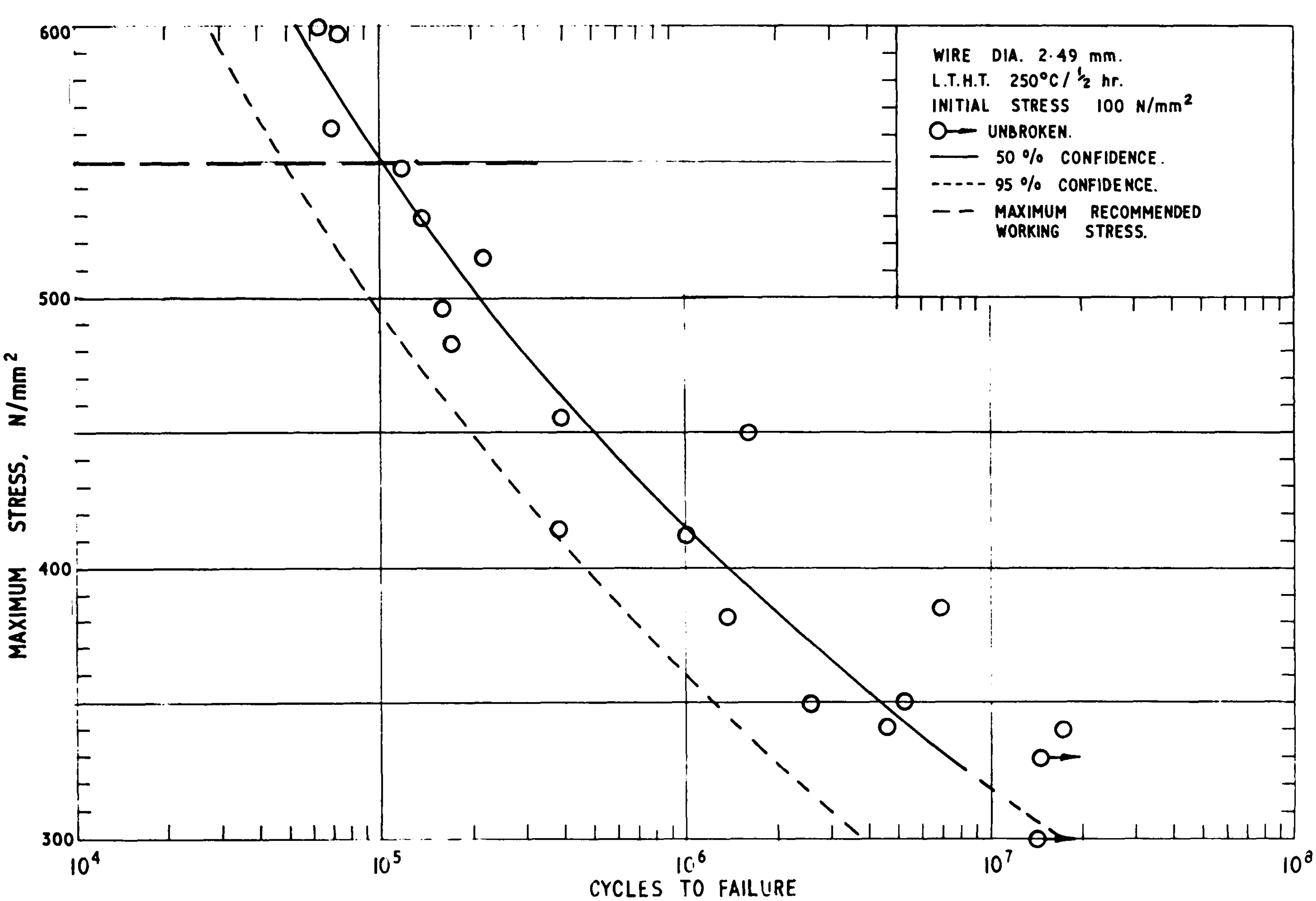

FIG. 1. S/N CURVE FOR UNPEENED SPRINGS OF HARD DRAWN TITANIUM 318.

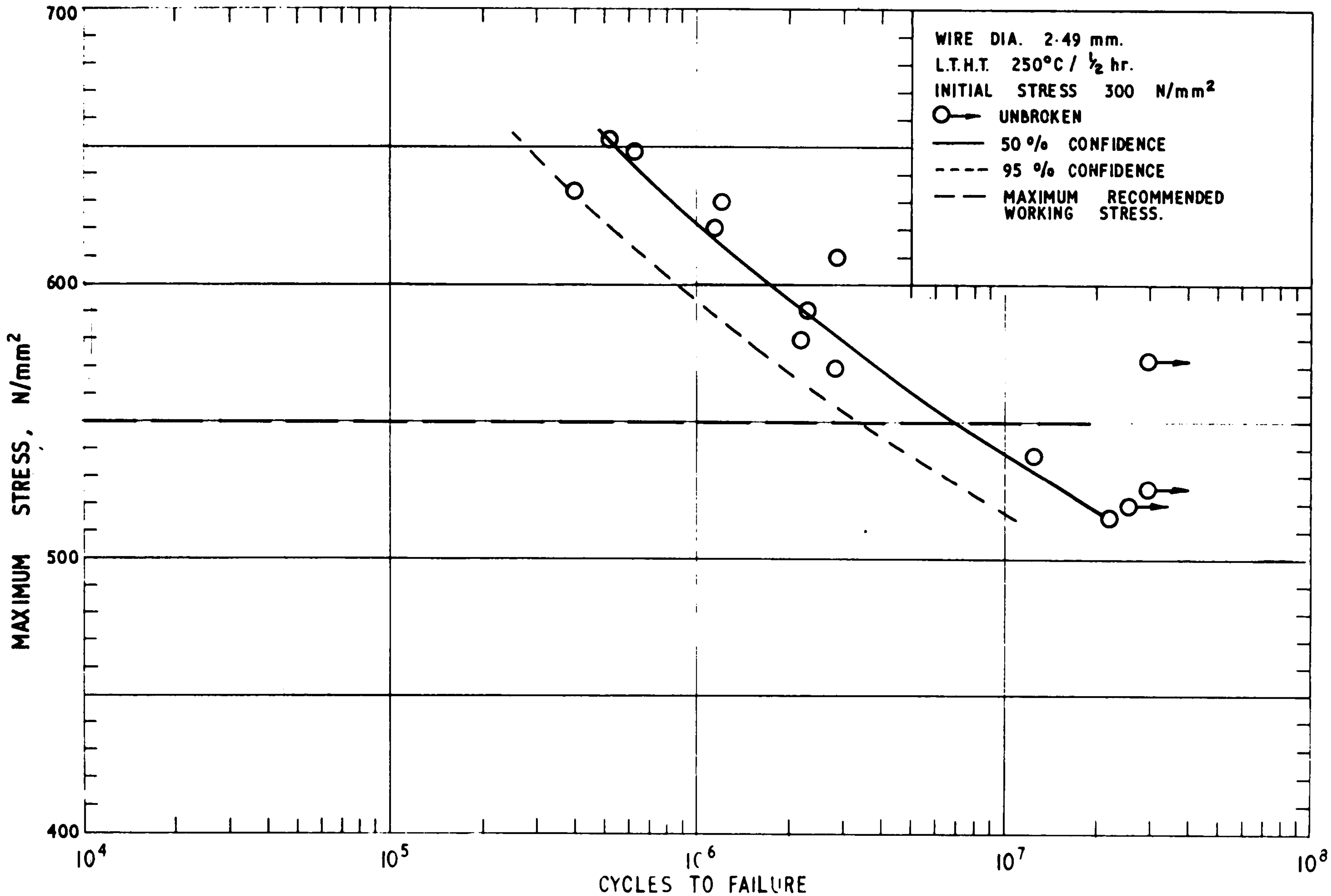

FIG. 2 S/N CURVE FOR UNPEENED SPRINGS OF HARD DRAWN TITANIUM 318.

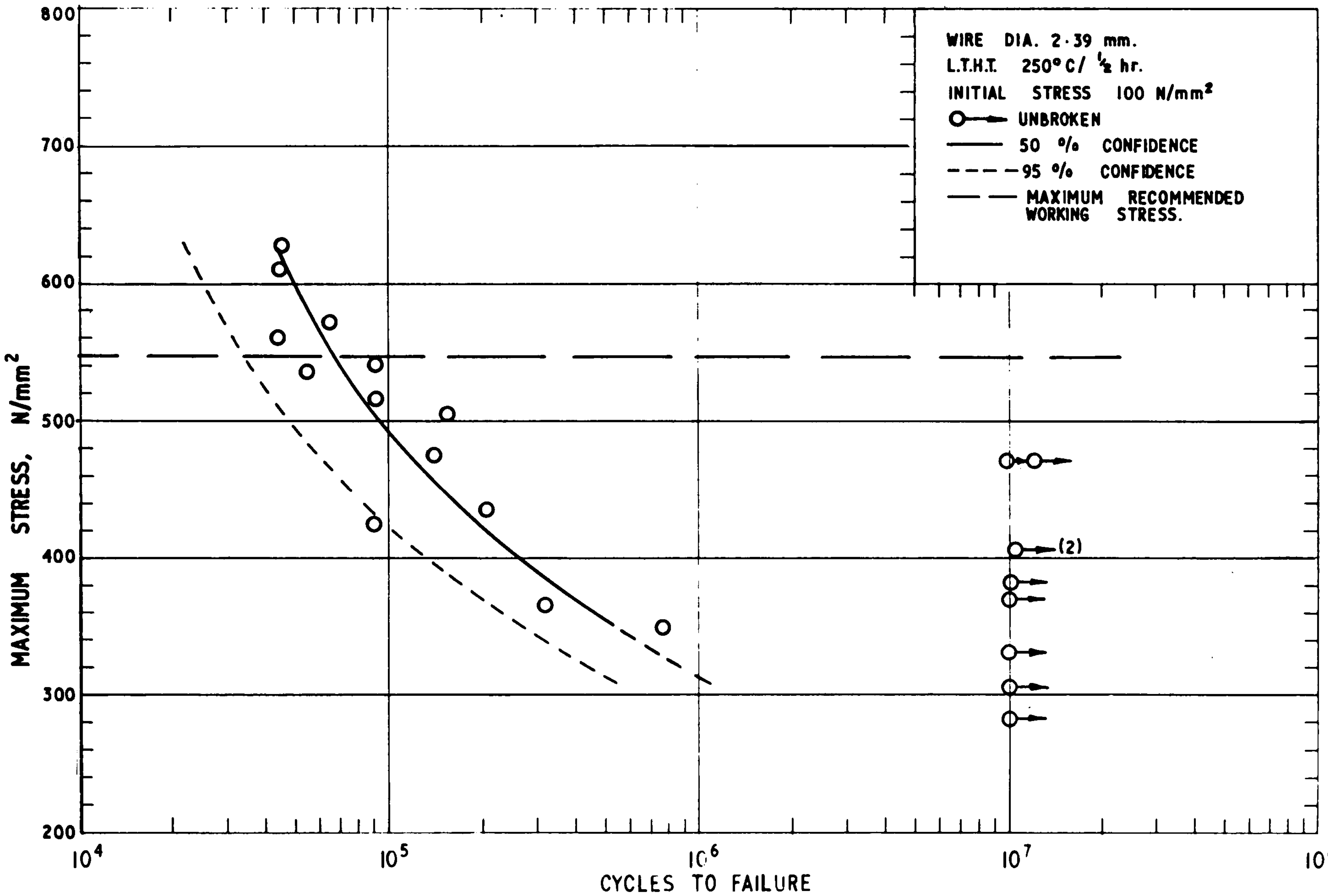

FIG. 3 S/N CURVE FOR UNPEENED SPRINGS OF SOLUTION TREATED AND AGED TITANIUM 318.

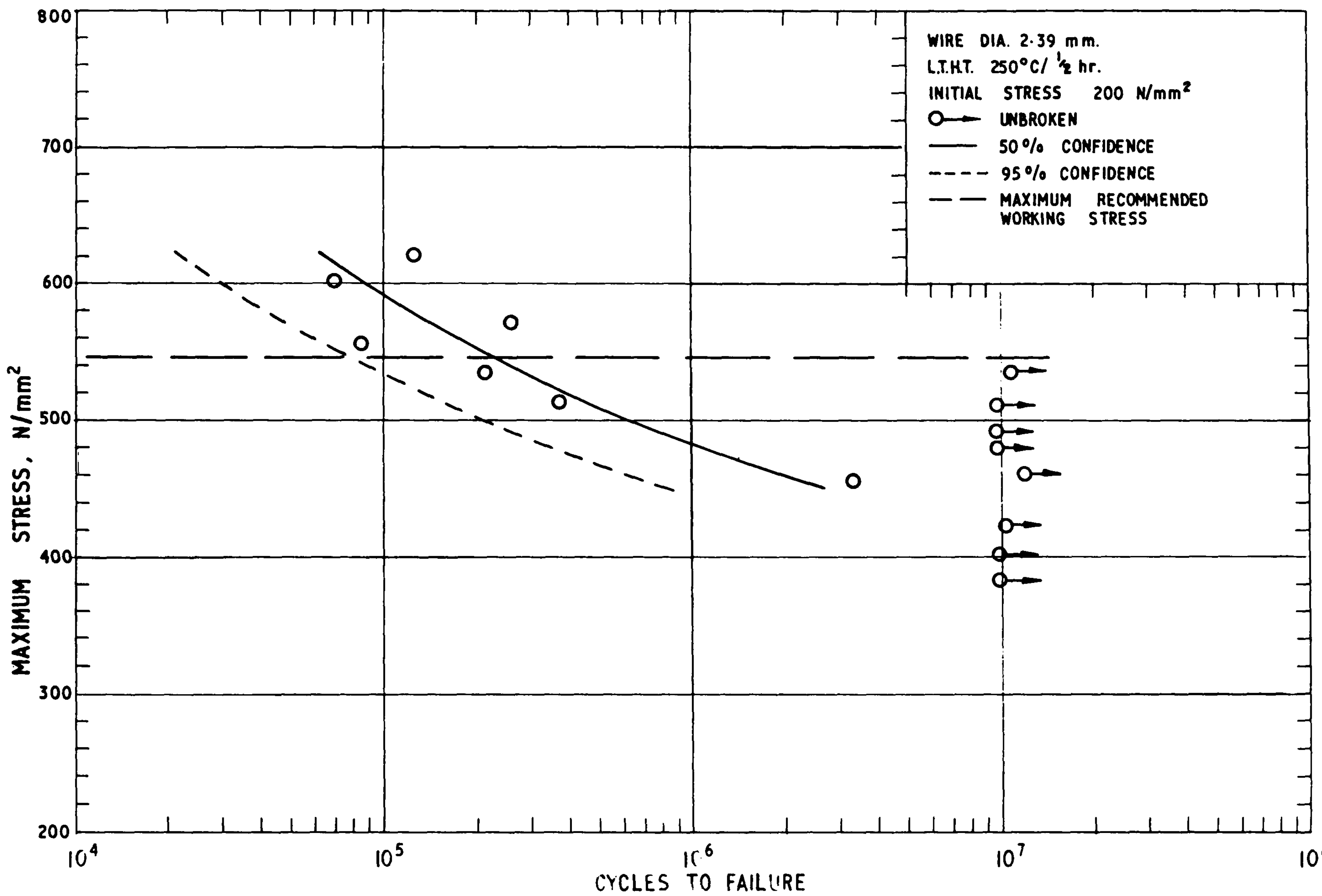

FIG. 4 S/N CURVE FOR UNPEENED SPRINGS OF SOLUTION TREATED AND AGED TITANIUM 318.

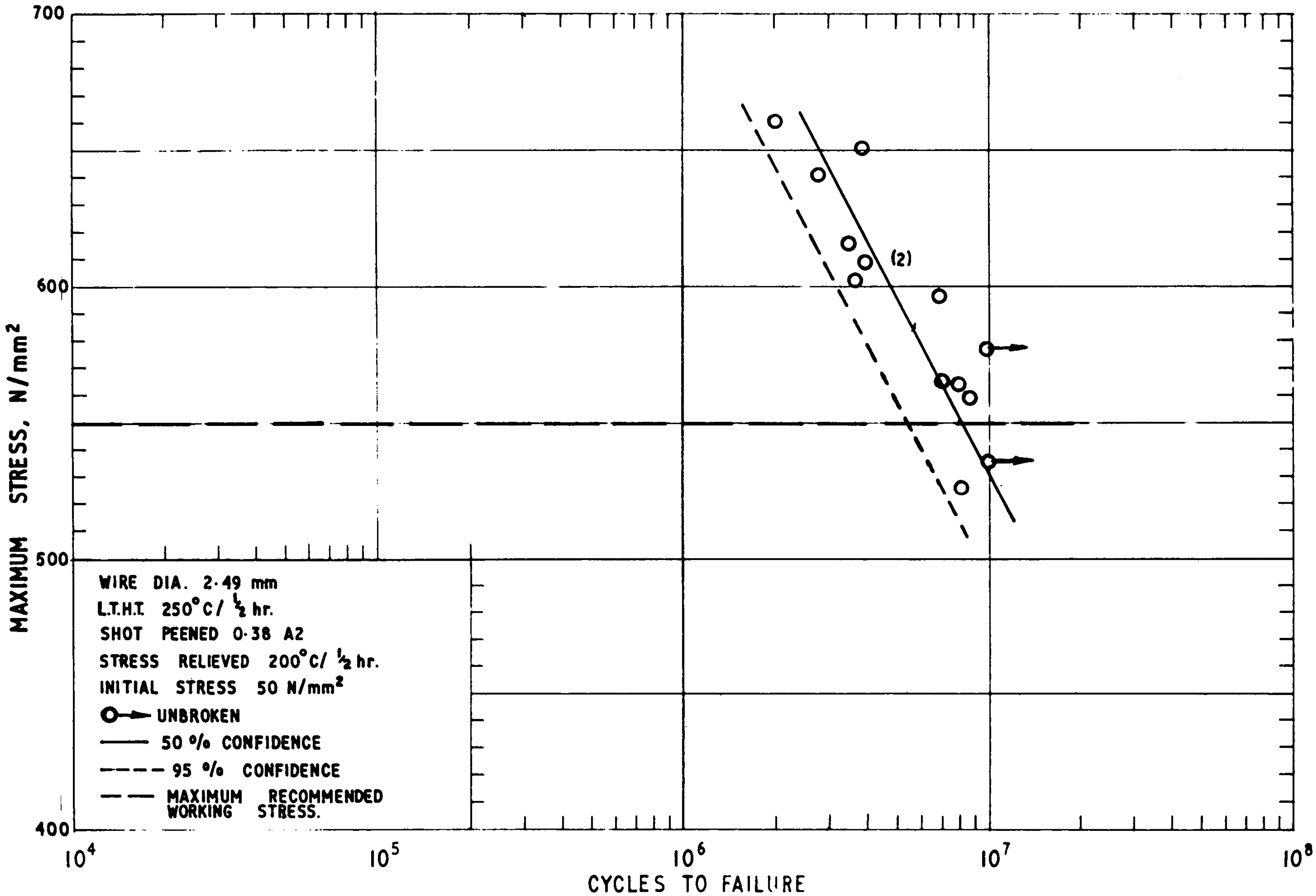

FIG. 5 S/N CURVE FOR SHOT PEENED SPRINGS OF HARD DRAWN TITANIUM 318.

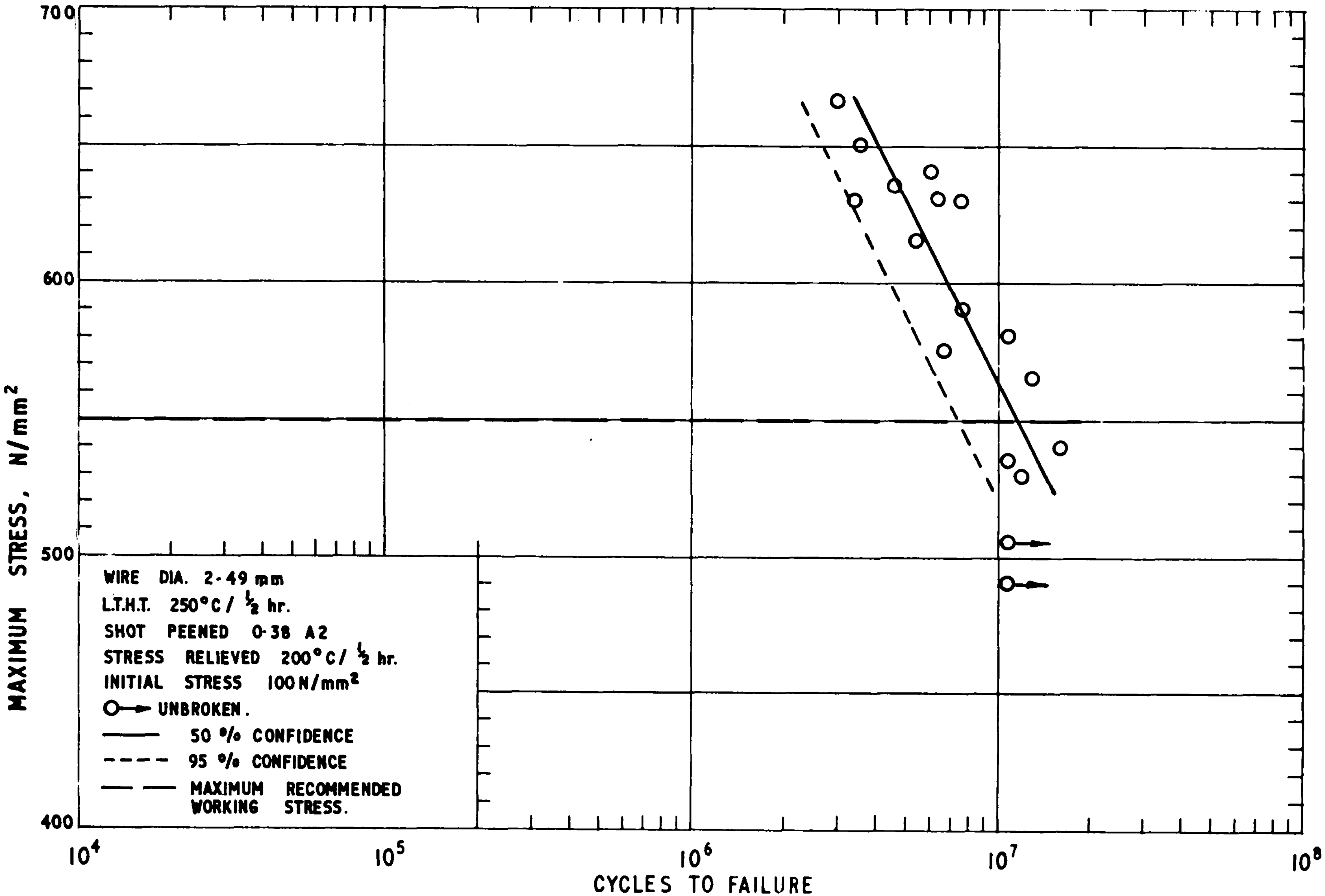

FIG. 6 S/N CURVE FOR SHOT PEENED SPRINGS OF HARD DRAWN TITANIUM 318.

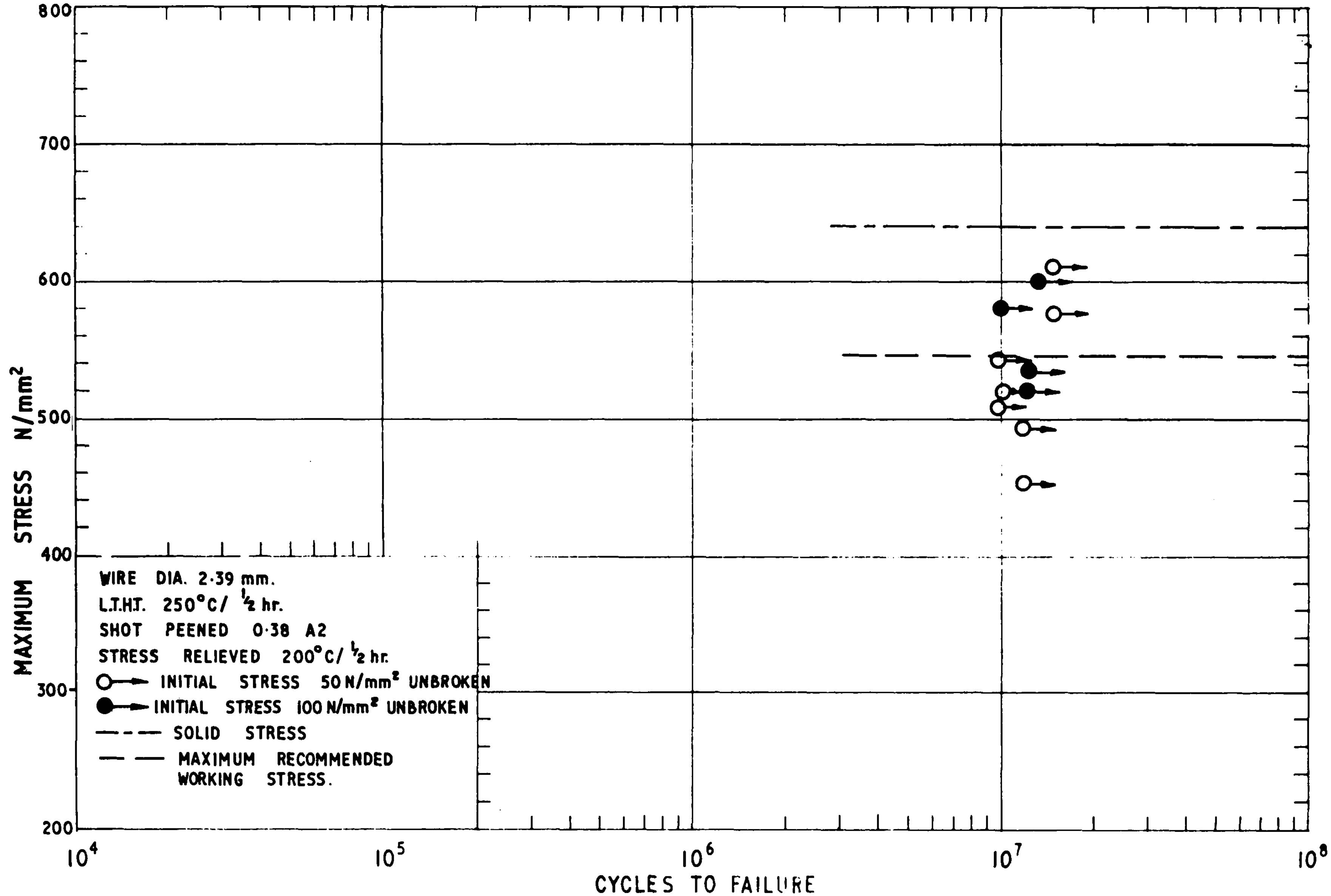

FIG. 7 S/N DATA FOR SHOT PEENED SPRINGS OF SOLUTION TREATED AND AGED TITANIUM 318.

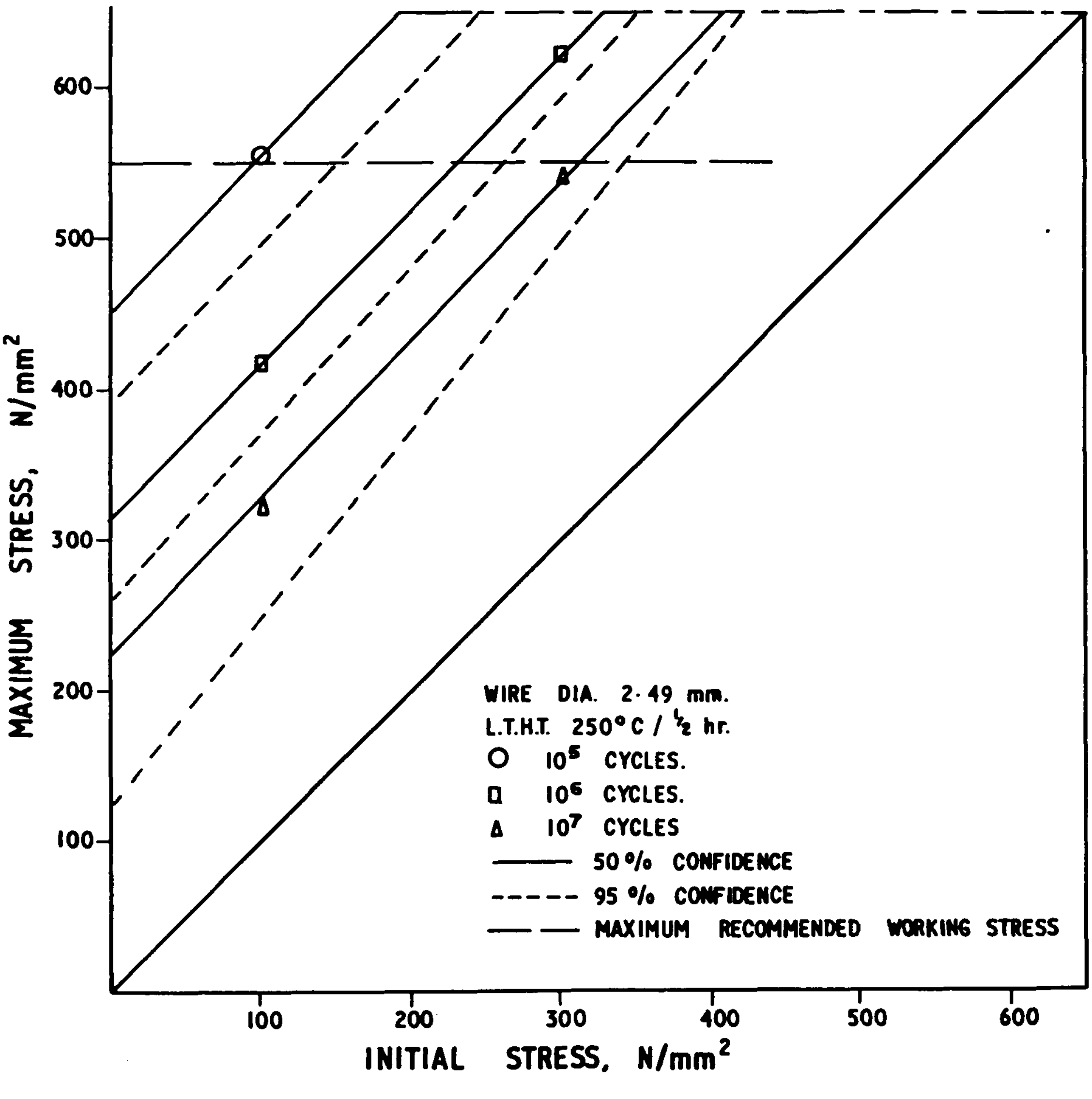

FIG. 8 MODIFIED GOODMAN DIAGRAM FOR UNPEENED SPRINGS OF HARD DRAWN TITANIUM 318.

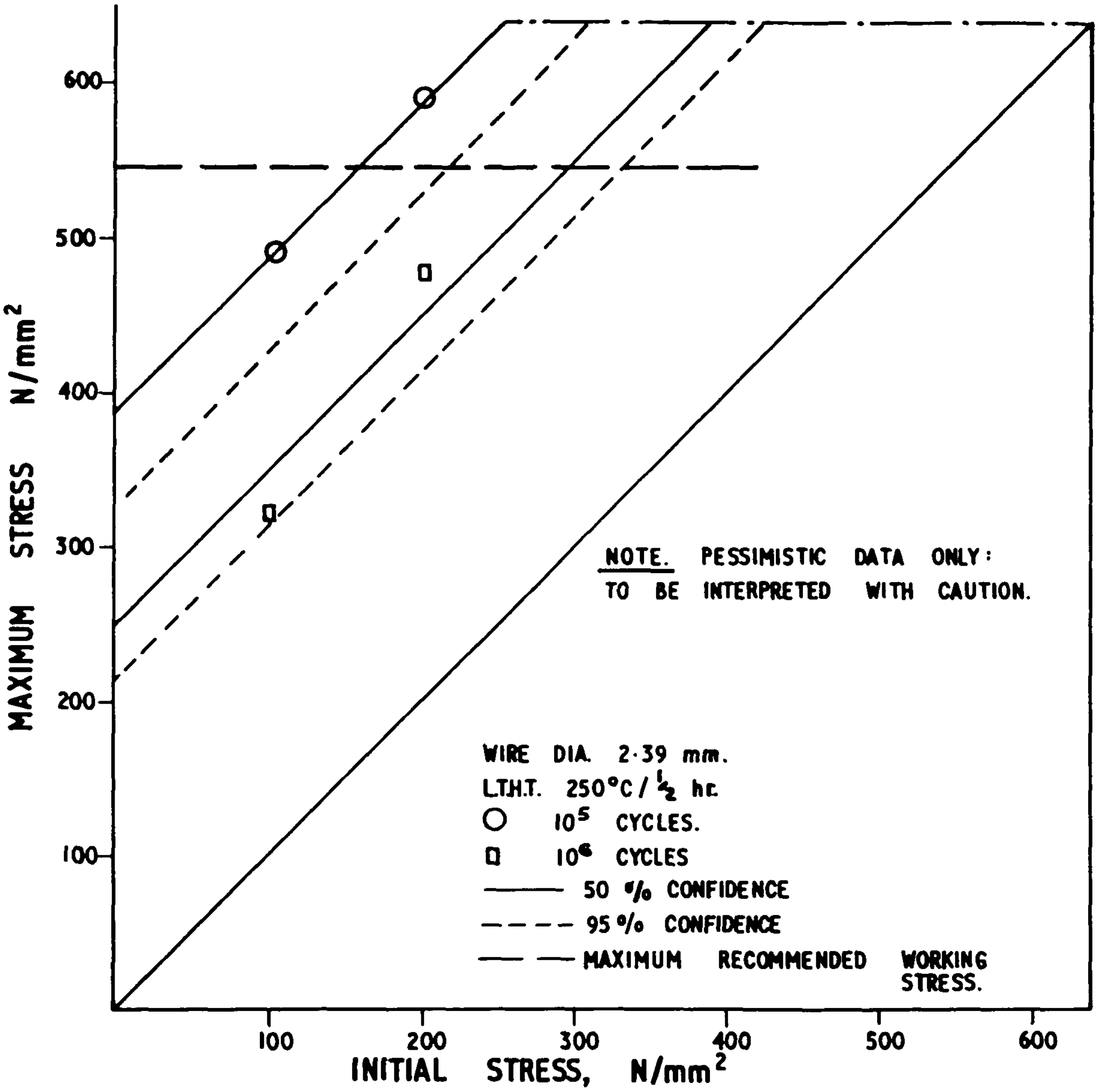

FIG. 9 MODIFIED GOODMAN DIAGRAM FOR UNPEENED SPRINGS OF SOLUTION TREATED AND AGED TITANIUM 318.

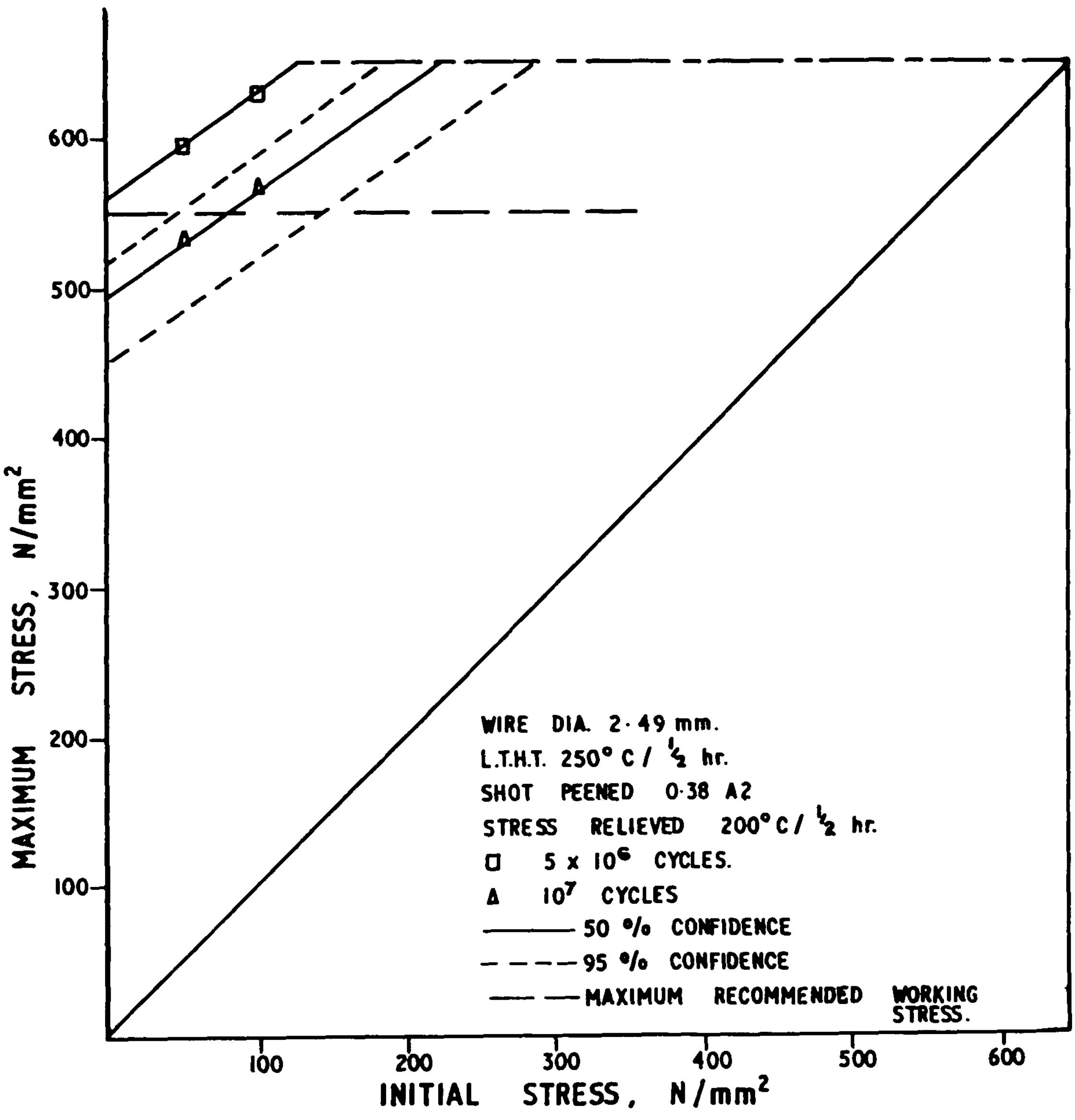

FIG. 10 MODIFIED GOODMAN DIAGRAM FOR SHOT PEENED SPRINGS OF HARD DRAWN TITANIUM 318.

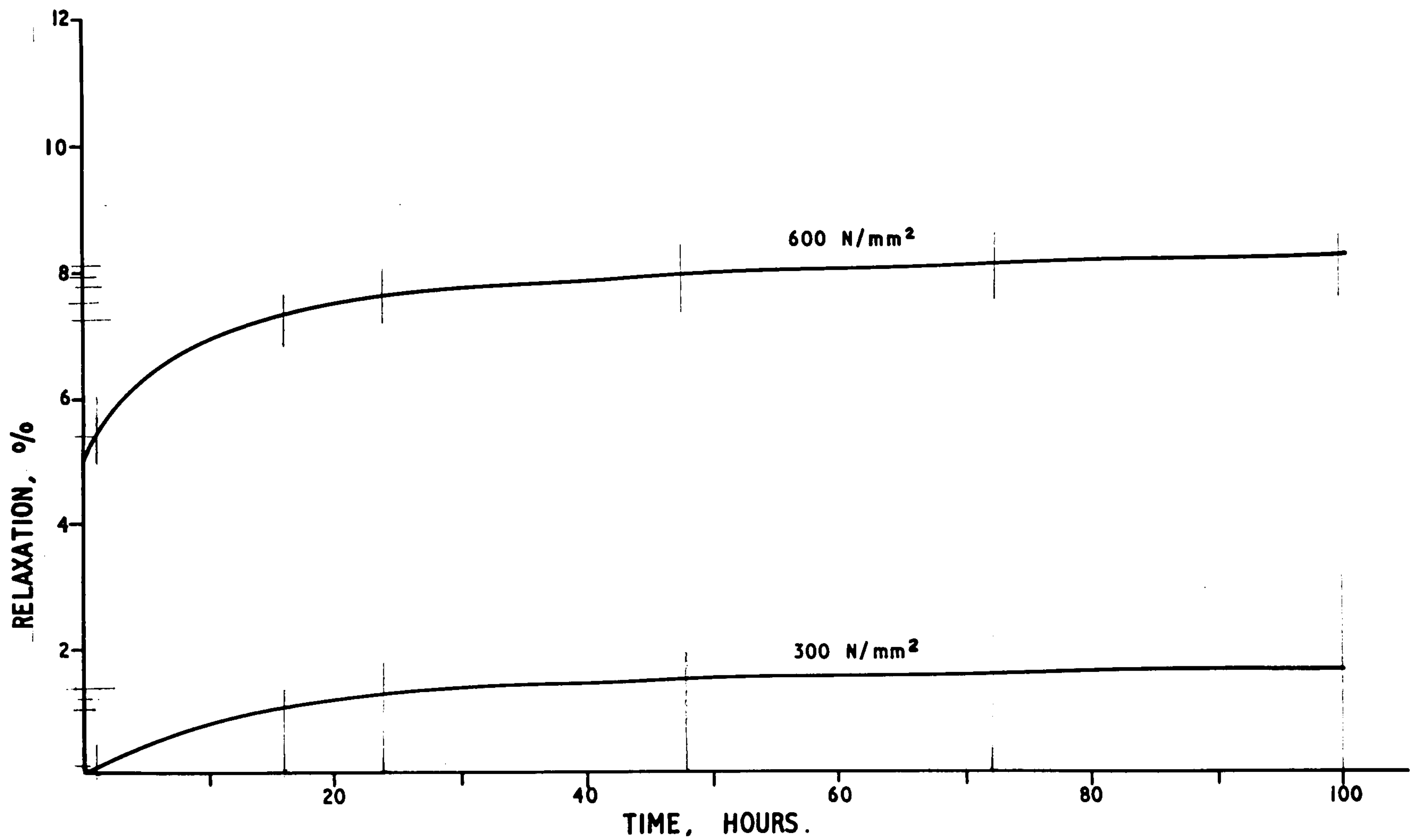

FIG. 11. TIME – RELAXATION CURVES FOR UNPEENED SPRINGS OF HARD DRAWN TITANIUM 318 AT 100° C.

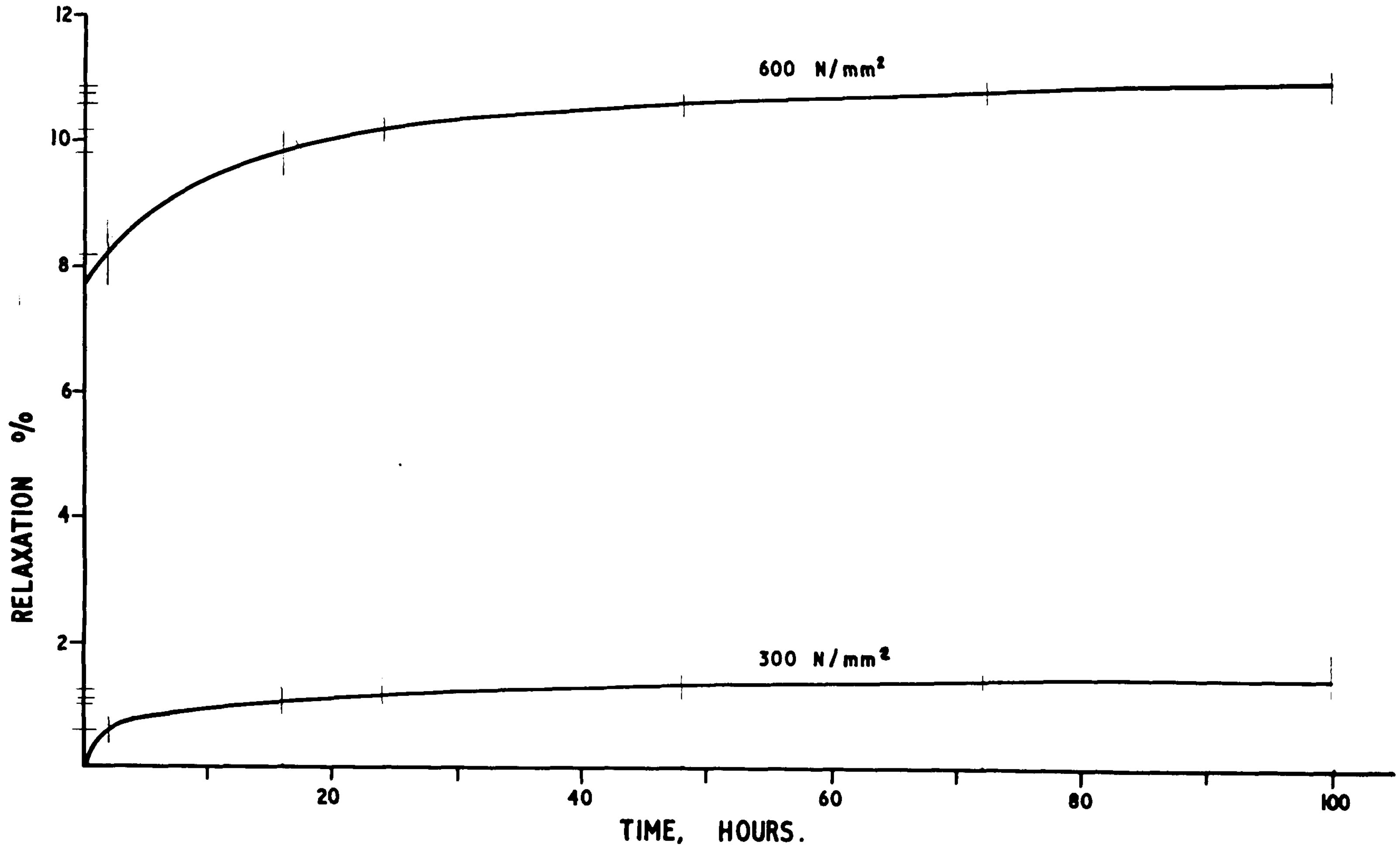

FIG. 12 TIME - RELAXATION CURVES FOR UNPEENED SPRINGS OF SOLUTION TREATED AND AGED TITANIUM 318 AT 100°C.

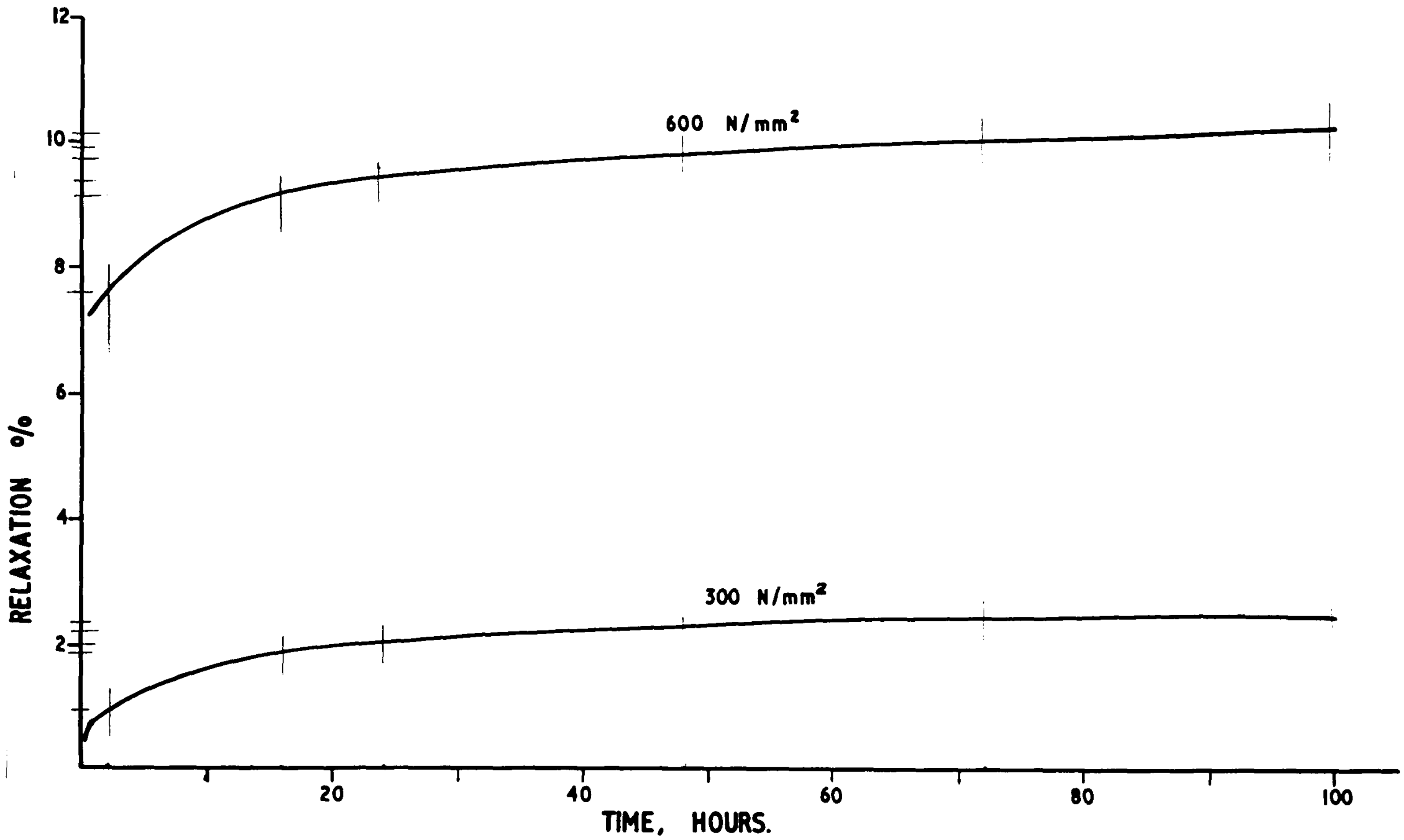

FIG. 13 TIME-RELAXATION CURVES FOR SHOT PEENED SPRINGS OF HARD DRAWN TITANIUM 318 AT 100° C.

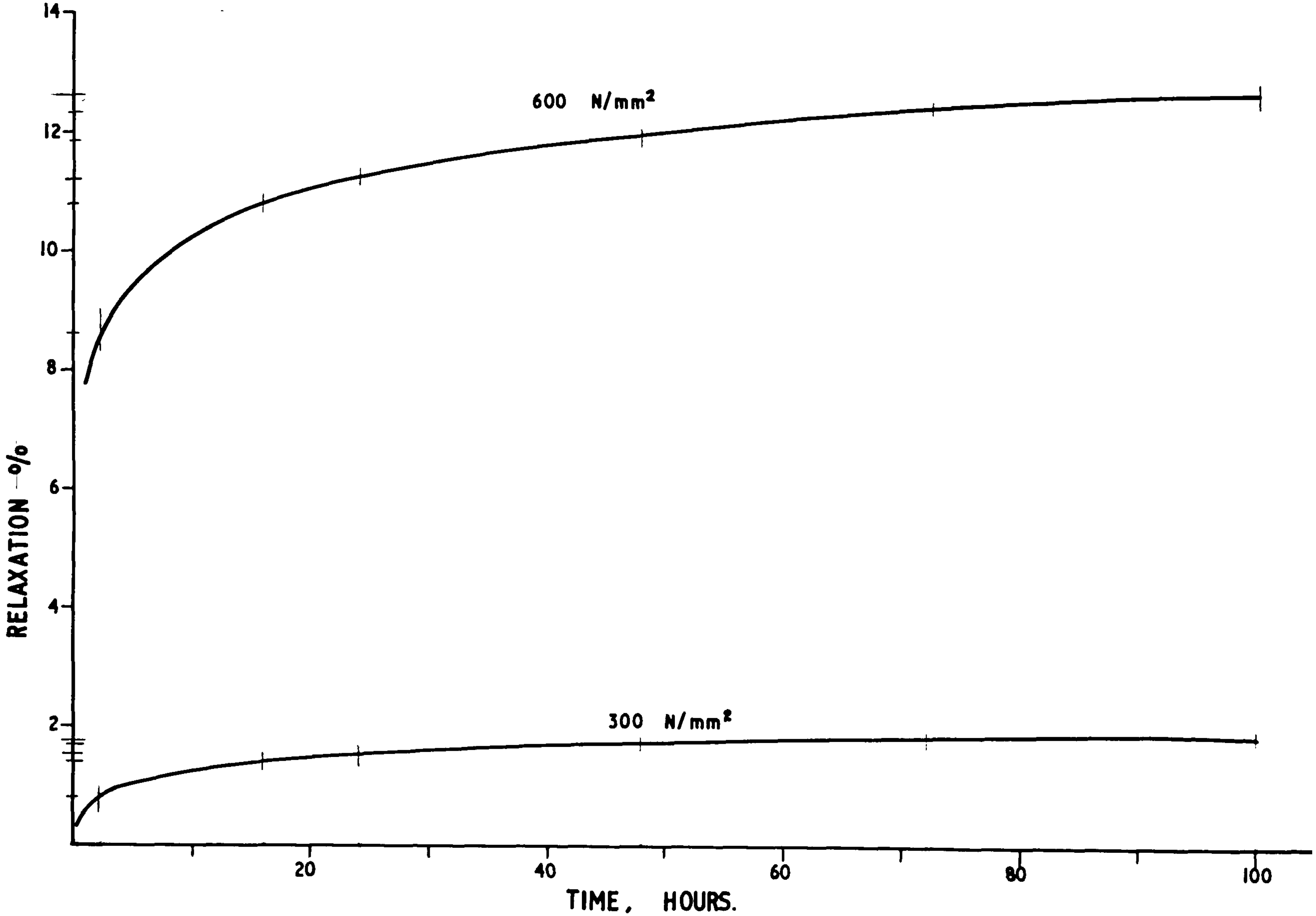

FIG. 14 TIME-RELAXATION CURVES FOR SHOT PEENED SPRINGS OF SOLUTION TREATED AND AGED TITANIUM 318 AT 100° C.

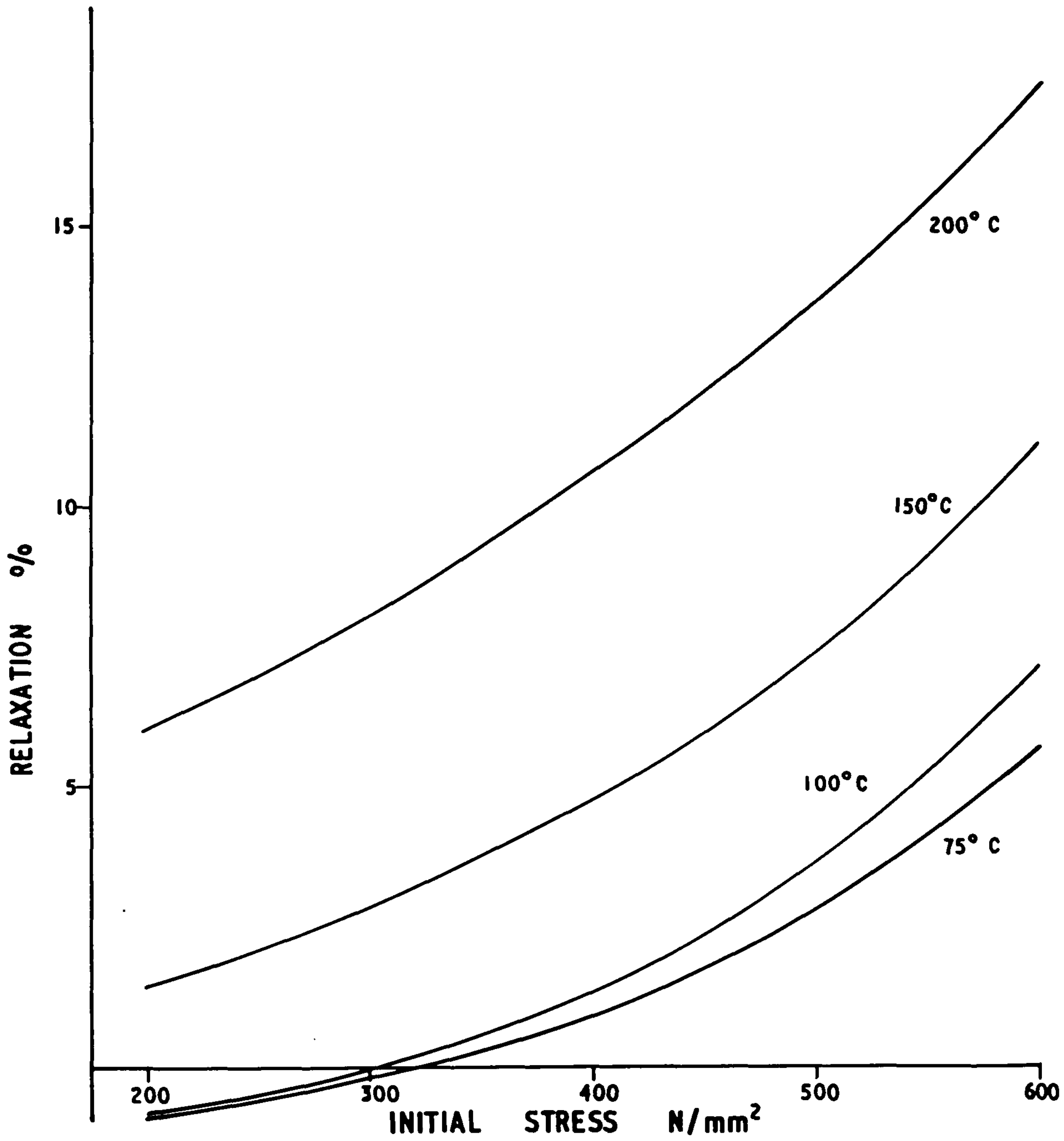

FIG. 15. STRESS-RELAXATION CURVES FOR UNPEENED SPRINGS OF HARD DRAWN TITANIUM 318.

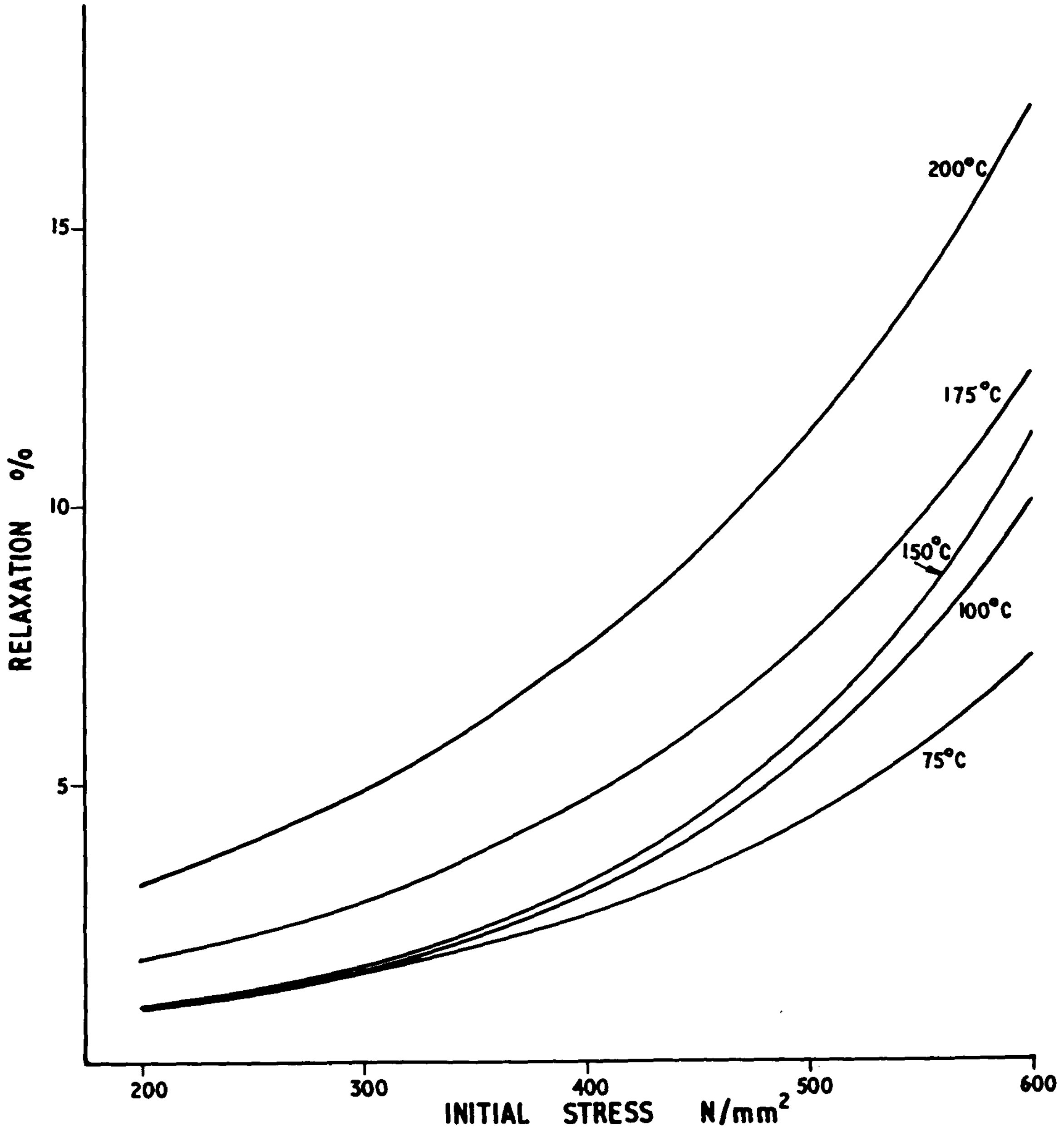

FIG. 16 STRESS - RELAXATION CURVES FOR UNPEENED SPRINGS OF SOLUTION TREATED AND AGED TITANIUM 318.

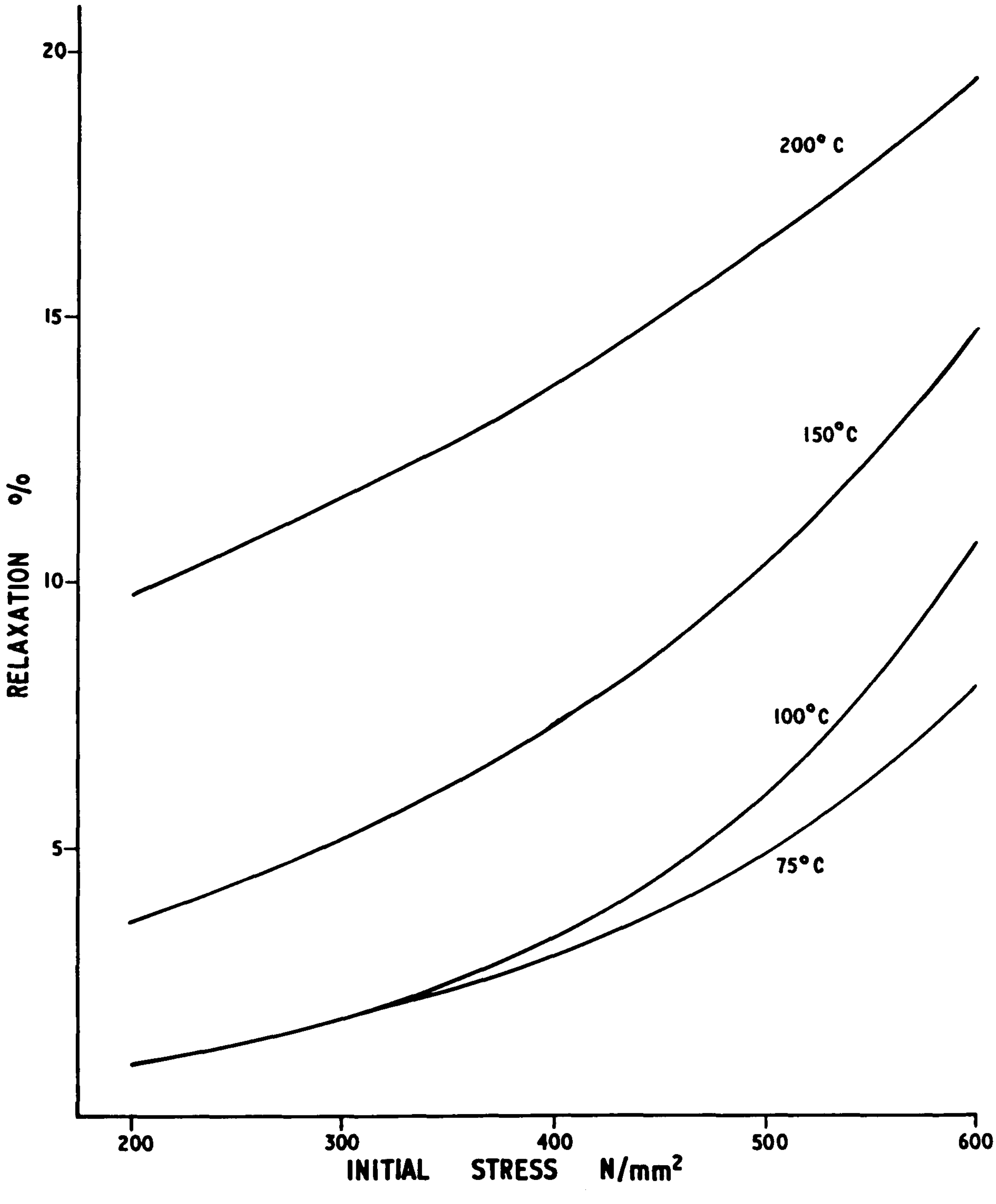

FIG. 17 STRESS-RELAXATION CURVES FOR SHOT PEENED SPRINGS OF HARD DRAWN TITANIUM 318.

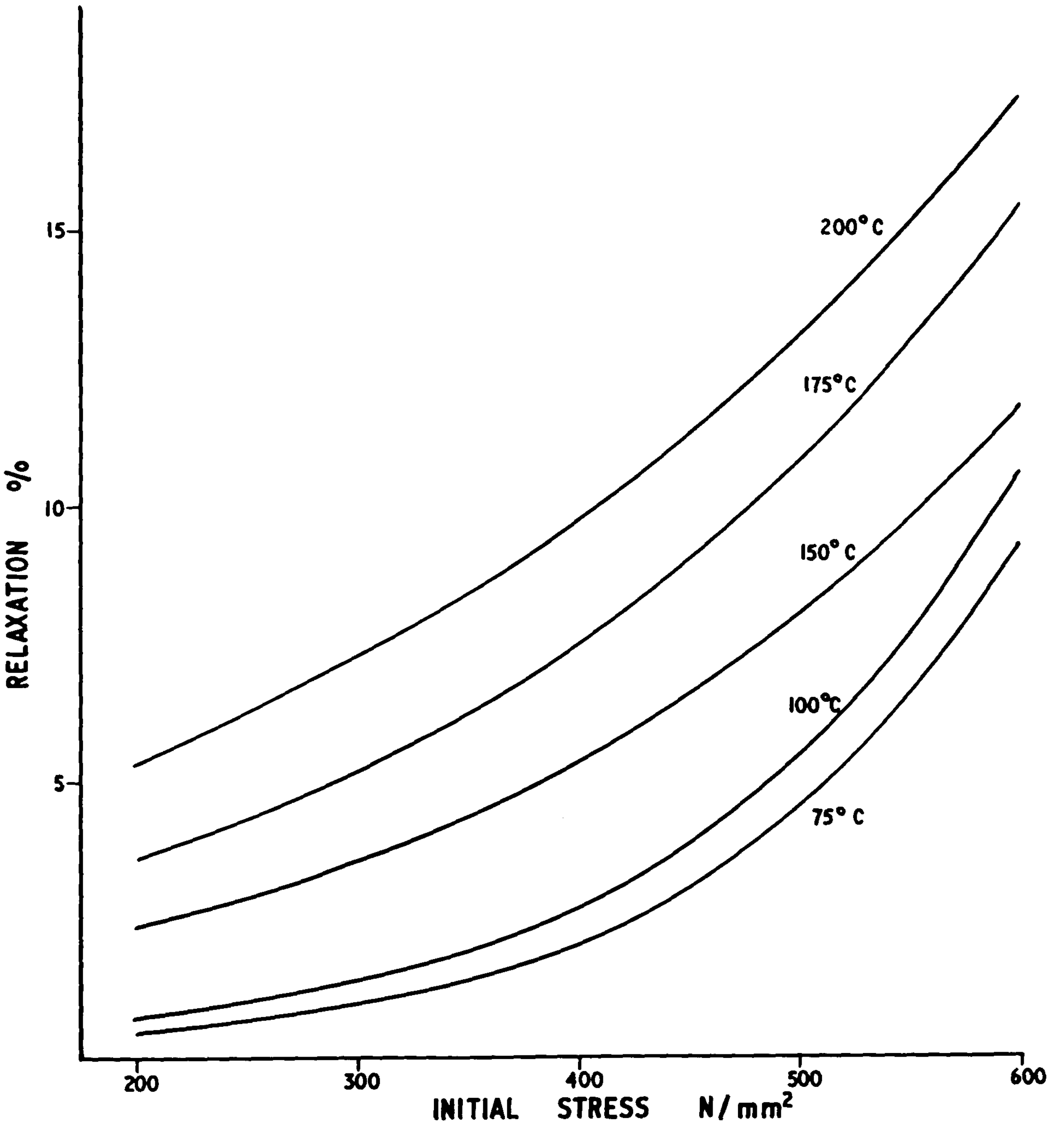

FIG. 18 STRESS-RELAXATION CURVES FOR SHOT PEENED SPRINGS OF SOLUTION TREATED AND AGED TITANIUM 318.

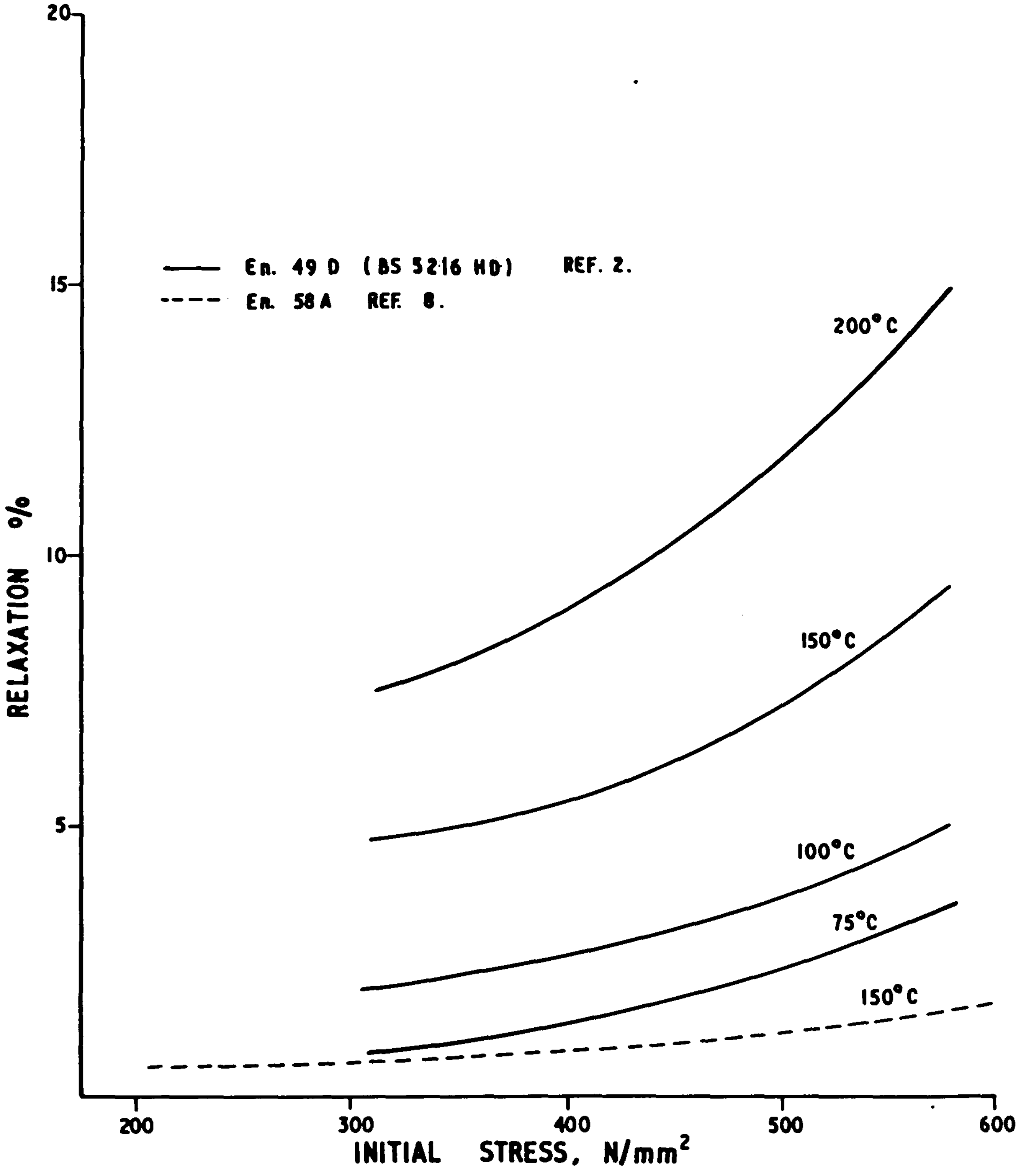

FIG. 19. STRESS - RELAXATION CURVES FOR En. 49 D AND En. 58 A SPRINGS.

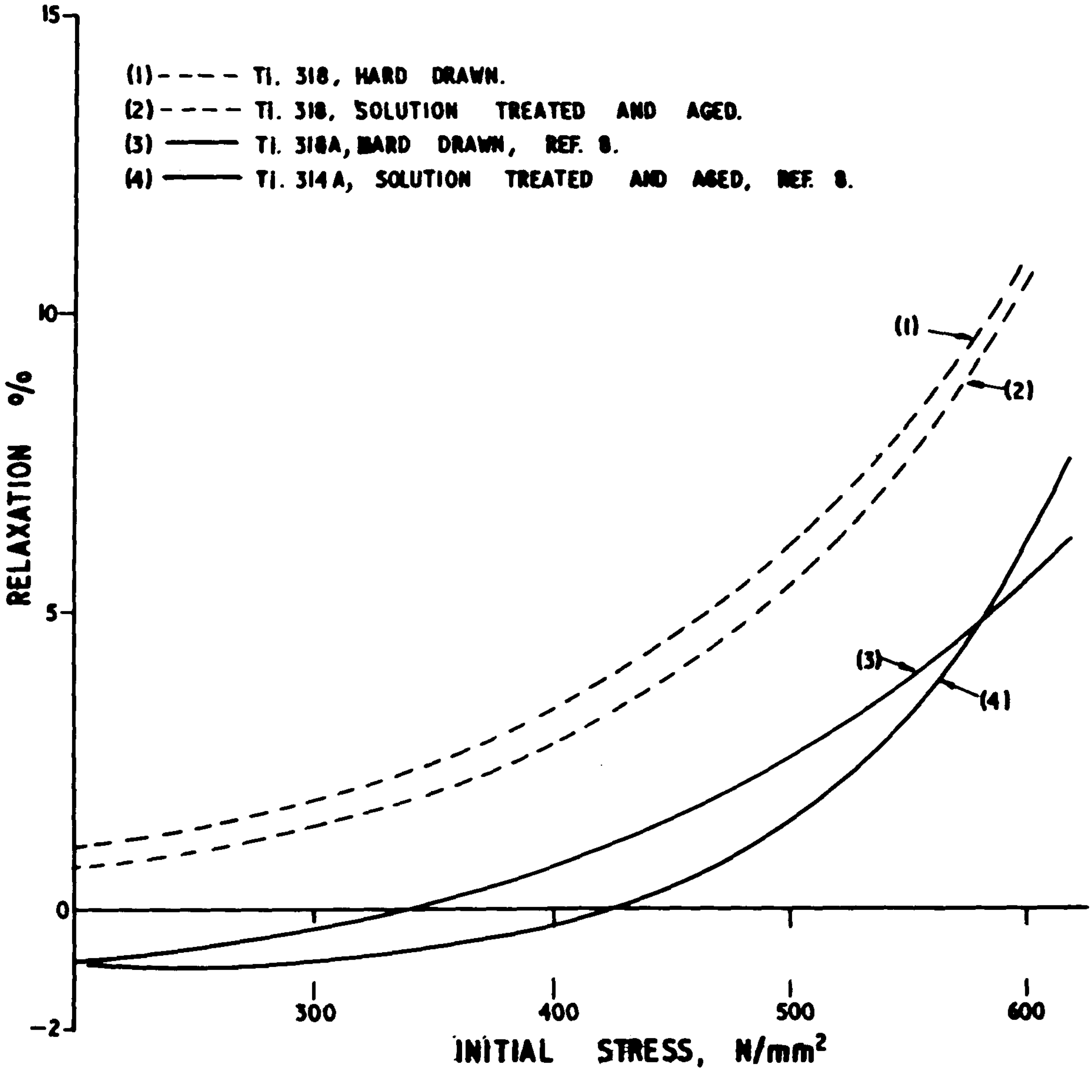

FIG. 20 COMPARATIVE STRESS-RELAXATION PROPERTIES OF SHOT-PEENED SPRINGS MADE FROM TITANIUM 318 AND TITANIUM 314 A, AT 100° C.

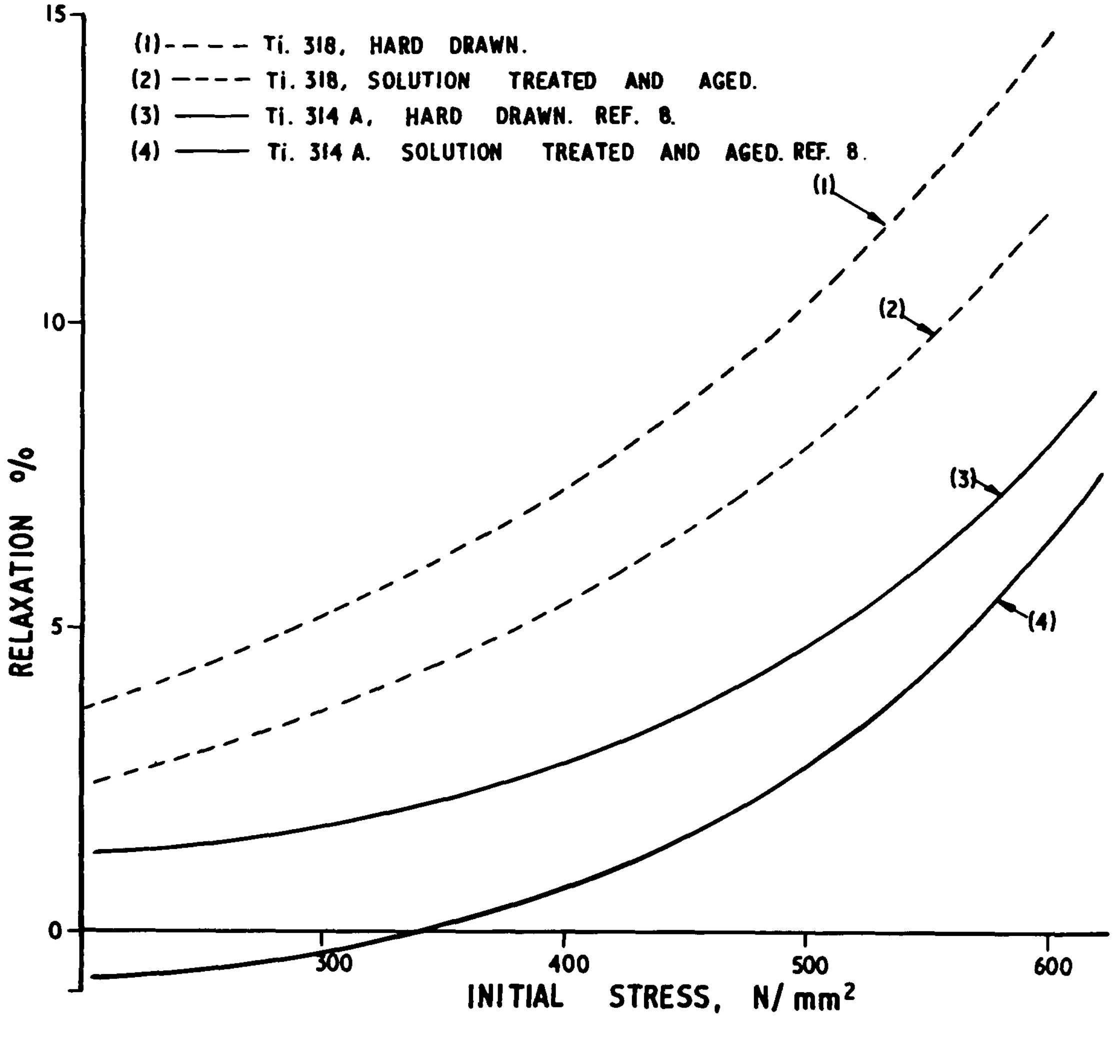

FIG. 21. COMPARATIVE STRESS - RELAXATION PROPERTIES OF SHOT - PEENED SPRINGS, MADE FROM TITANIUM 318 AND TITANIUM 314 A, AT 150°C.

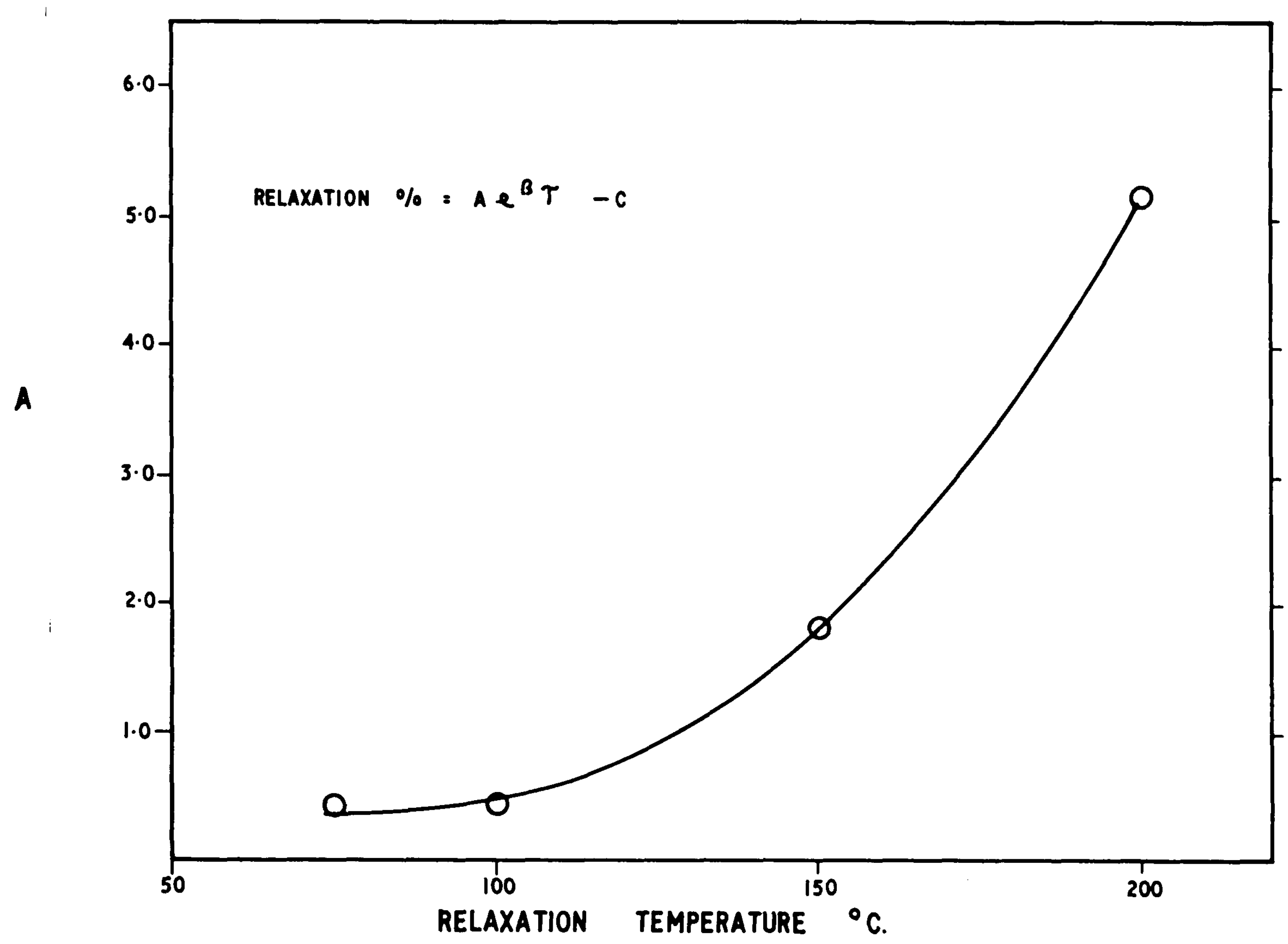

FIG. 22 ANALYTICAL CONSTANT, 'A' FOR UNPEENED SPRINGS OF HARD DRAWN TITANIUM 318 SHOWN PLOTTED AS A FUNCTION OF STRESS - RELAXATION TEMPERATURE.

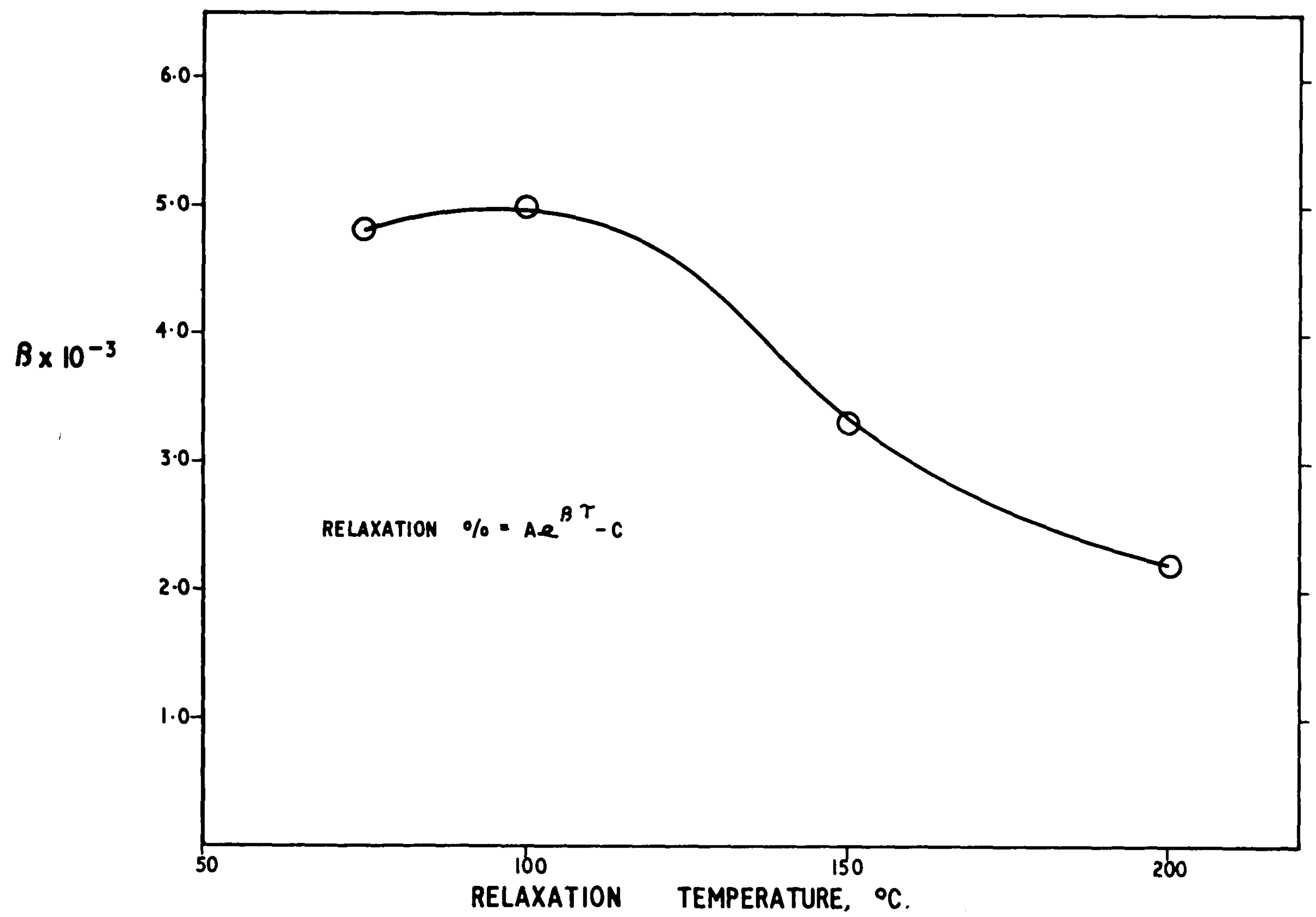

FIG. 23 ANALYTICAL CONSTANT, 'β', FOR UNPEENED SPRINGS OF HARD DRAWN TITANIUM 318 SHOWN PLOTTED AS A FUNCTION OF STRESS - RELAXATION TEMPERATURE.

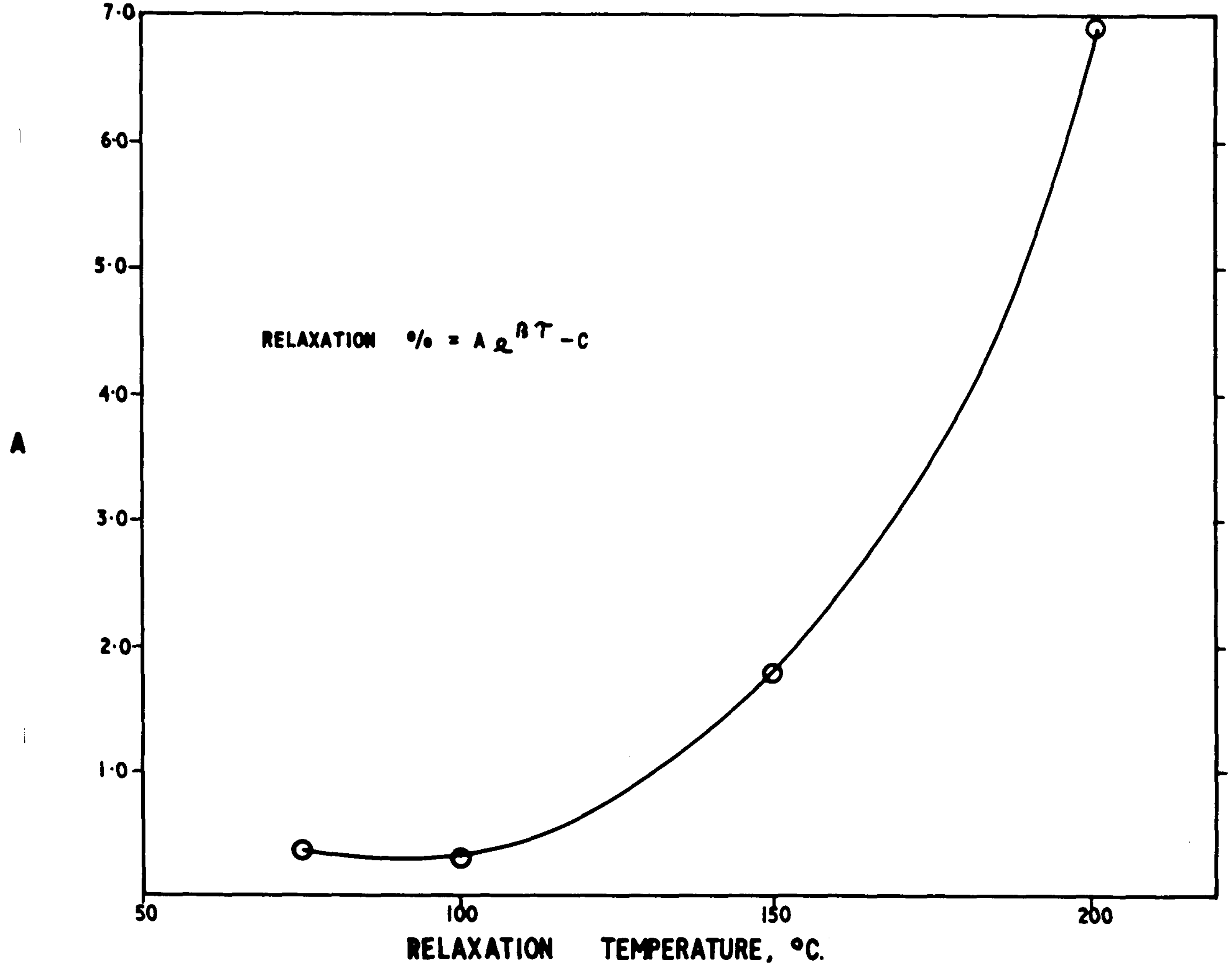

FIG. 24 ANALYTICAL CONSTANT, 'A', FOR SHOT PEENED SPRINGS OF HARD DRAWN TITANIUM 318 SHOWN PLOTTED AS A FUNCTION OF STRESS – RELAXATION TEMPERATURE.

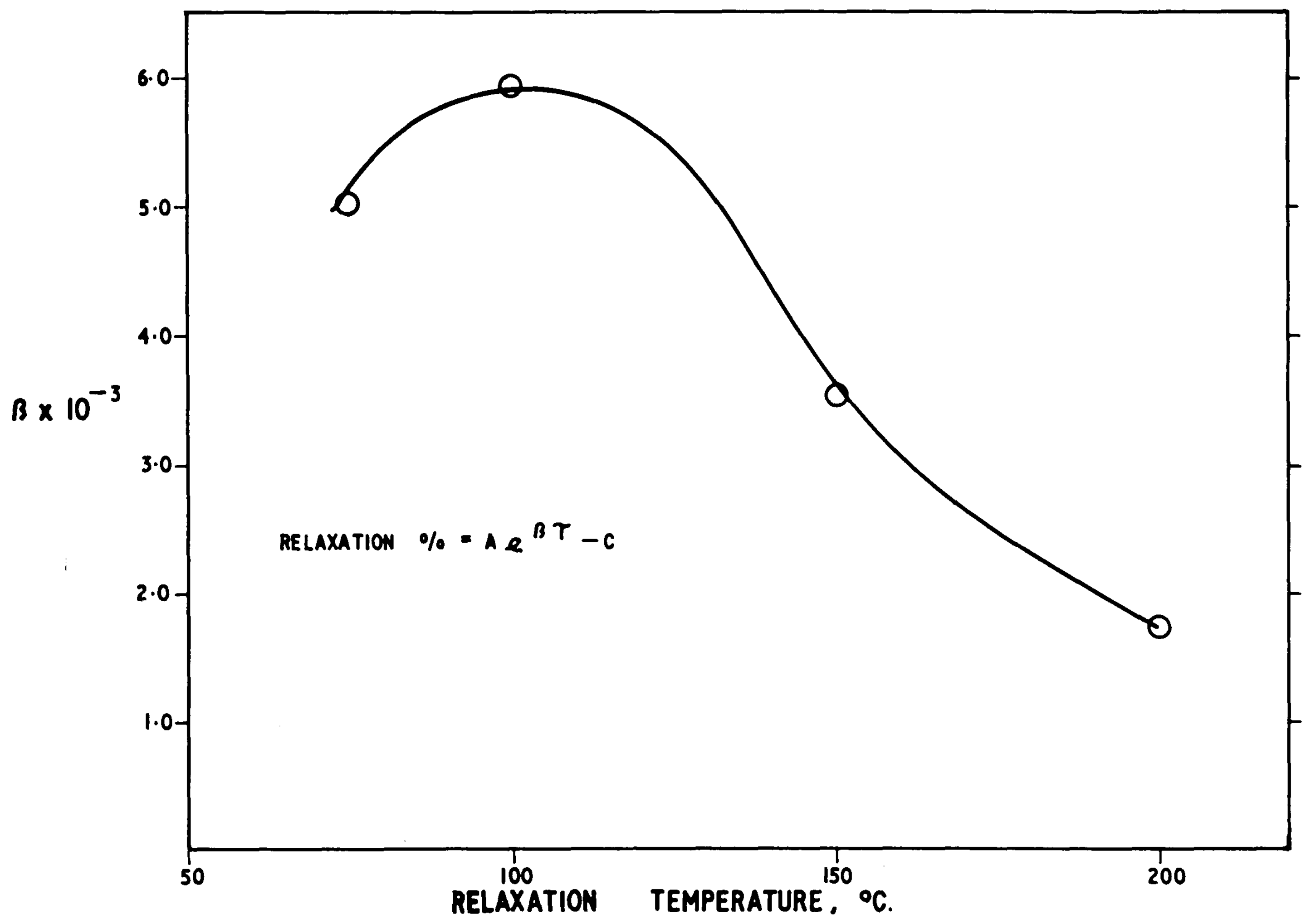

FIG. 25 ANALYTICAL CONSTANT, 'ß', FOR SHOT PEENED SPRINGS OF HARD DRAWN TITANIUM 318 SHOWN PLOTTED AS A FUNCTION OF STRESS - RELAXATION TEMPERATURE.

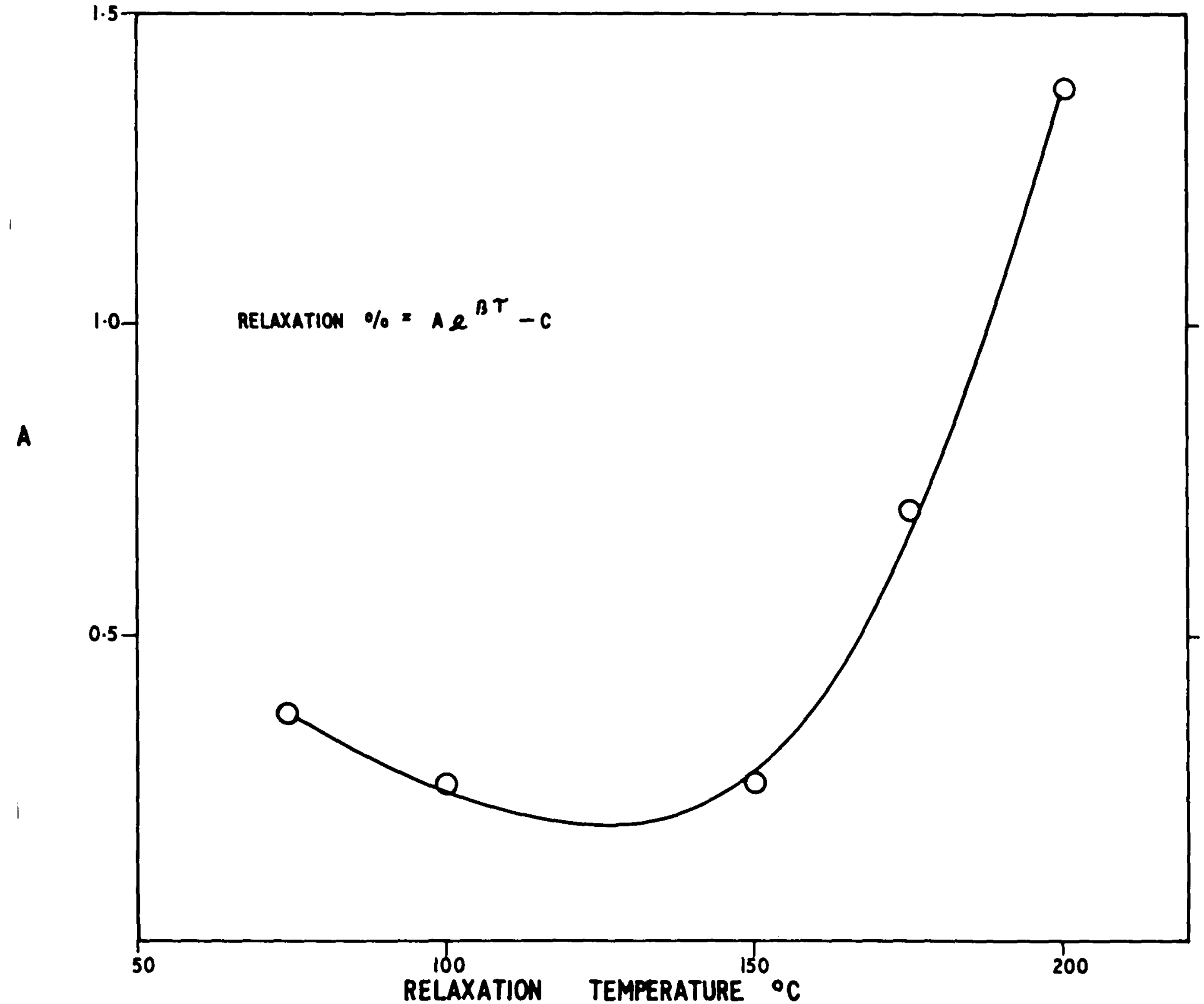

FIG. 26 ANALYTICAL CONSTANT, 'A', FOR UNPEENED SPRINGS OF SOLUTION TREATED AND AGED TITANIUM 318 SHOWN PLOTTED AS A FUNCTION OF STRESS RELAXATION TEMPERATURE.

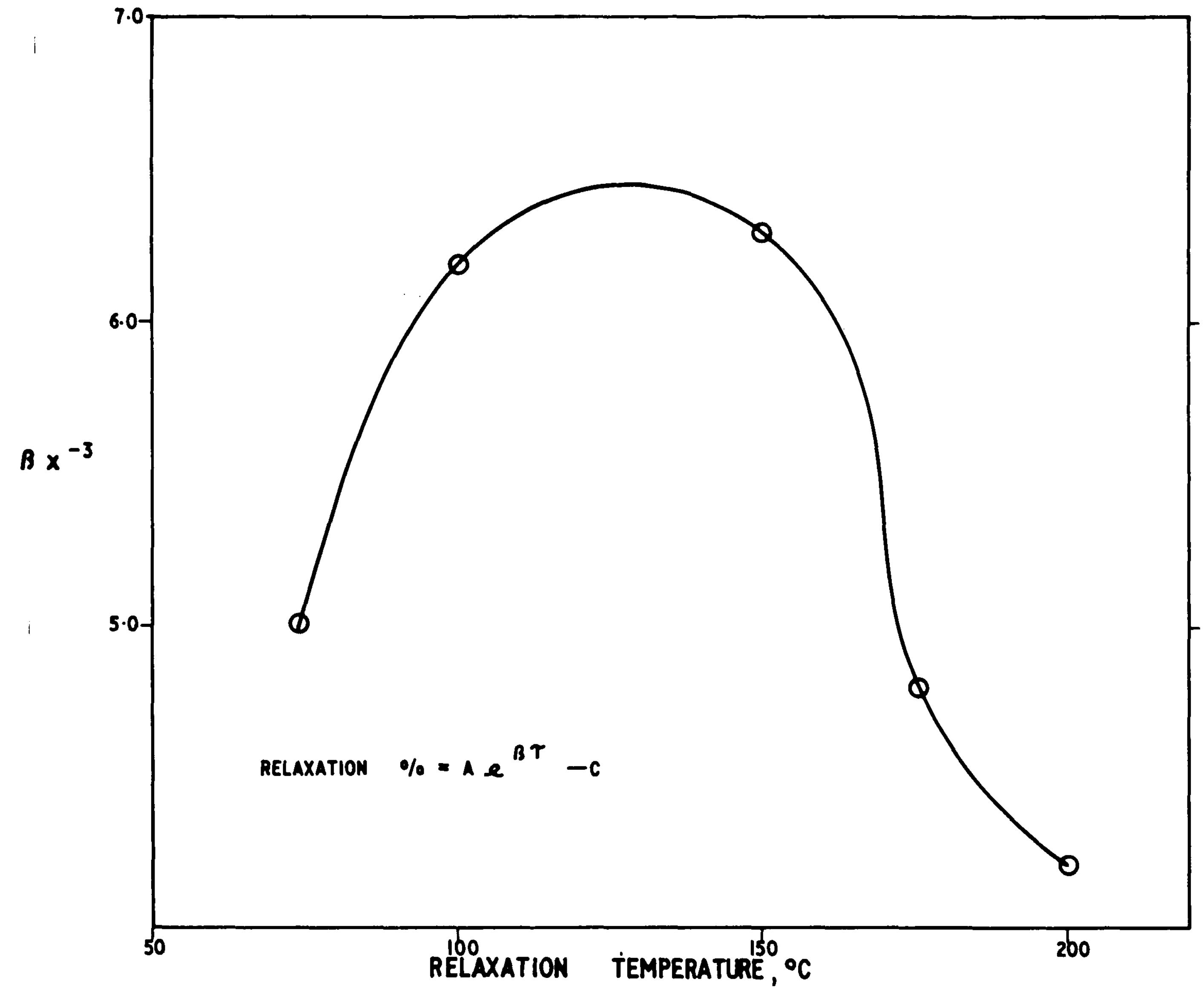

FIG. 27 ANALYTICAL CONSTANT, 'β', FOR UNPEENED SPRINGS OF SOLUTION TREATED AND AGED TITANIUM 318 SHOWN PLOTTED AS A FUNCTION OF STRESS-RELAXATION TEMPERATURE.

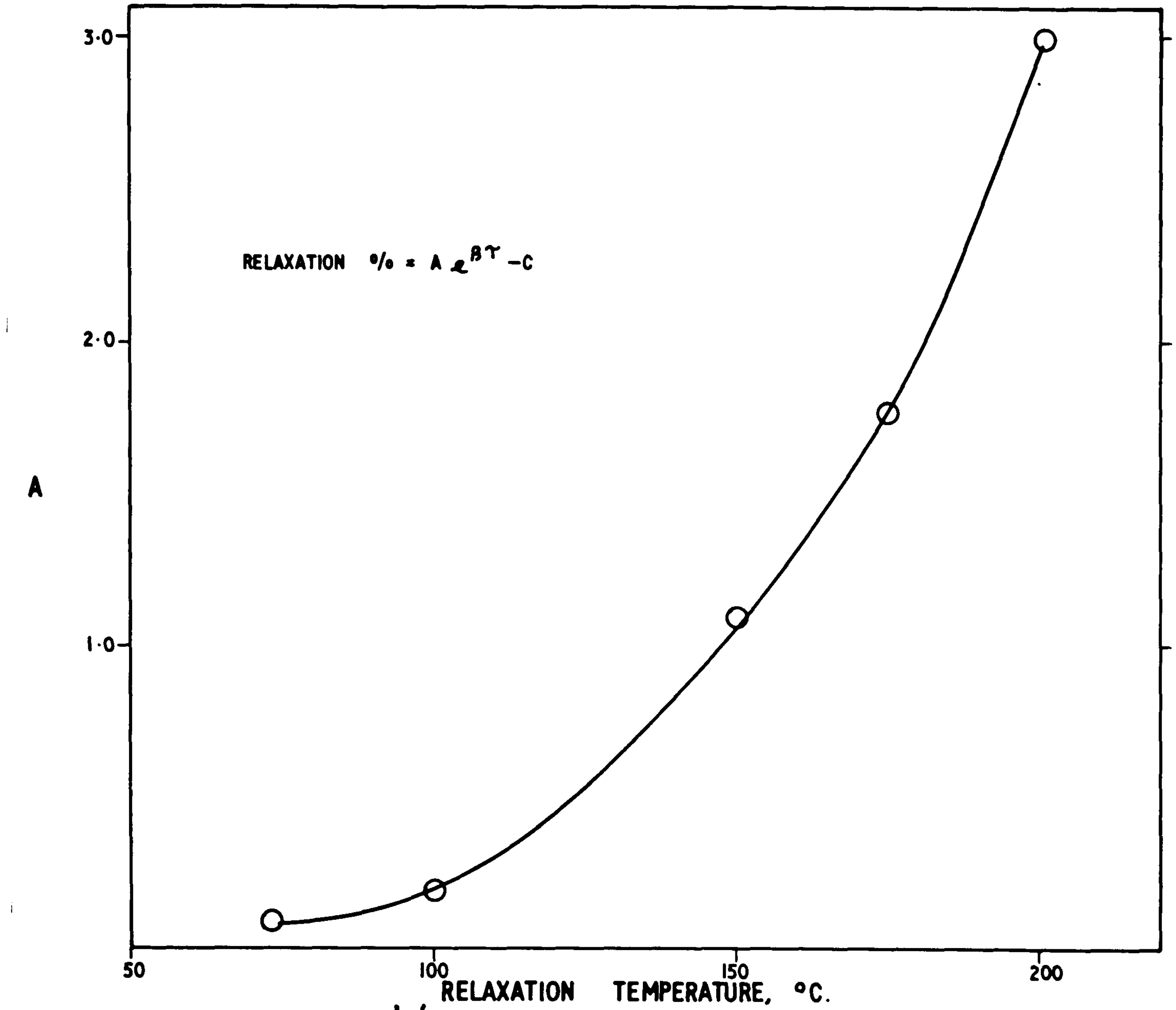

FIG. 28 ANALYTICAL CONSTANT 'A' FOR SHOT PEENED SPRINGS OF SOLUTION TREATED AND AGED TITANIUM 318 SHOWN PLOTTED AS A FUNCTION OF STRESS - RELAXATION TEMPERATURE.

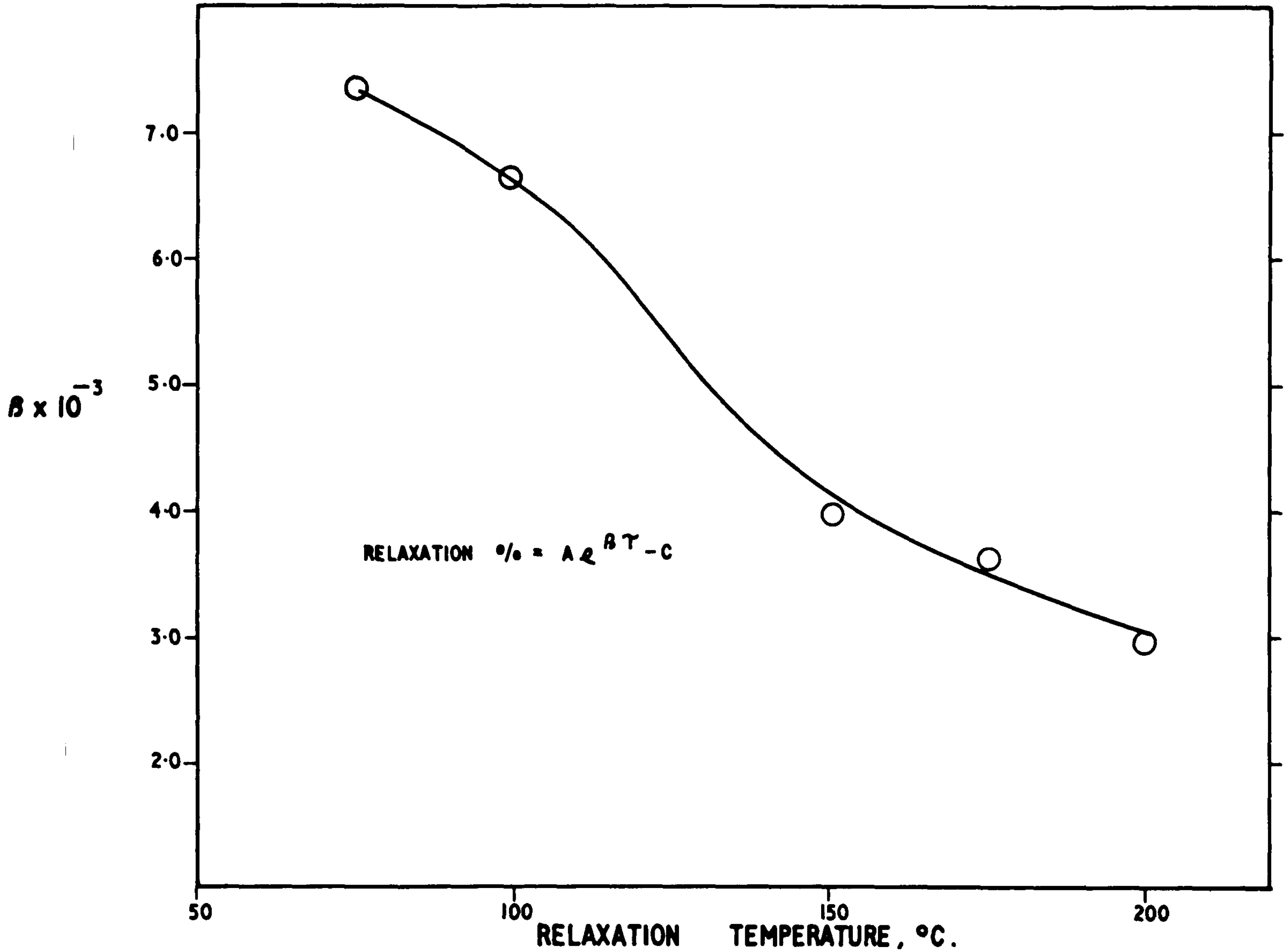

FIG. 29 ANALYTICAL CONSTANT, 'β', FOR SHOT PEENED SPRINGS OF SOLUTION TREATED AND AGED TITANIUM 318 SHOWN PLOTTED AS A FUNCTION OF STRESS-RELAXATION TEMPERATURE.

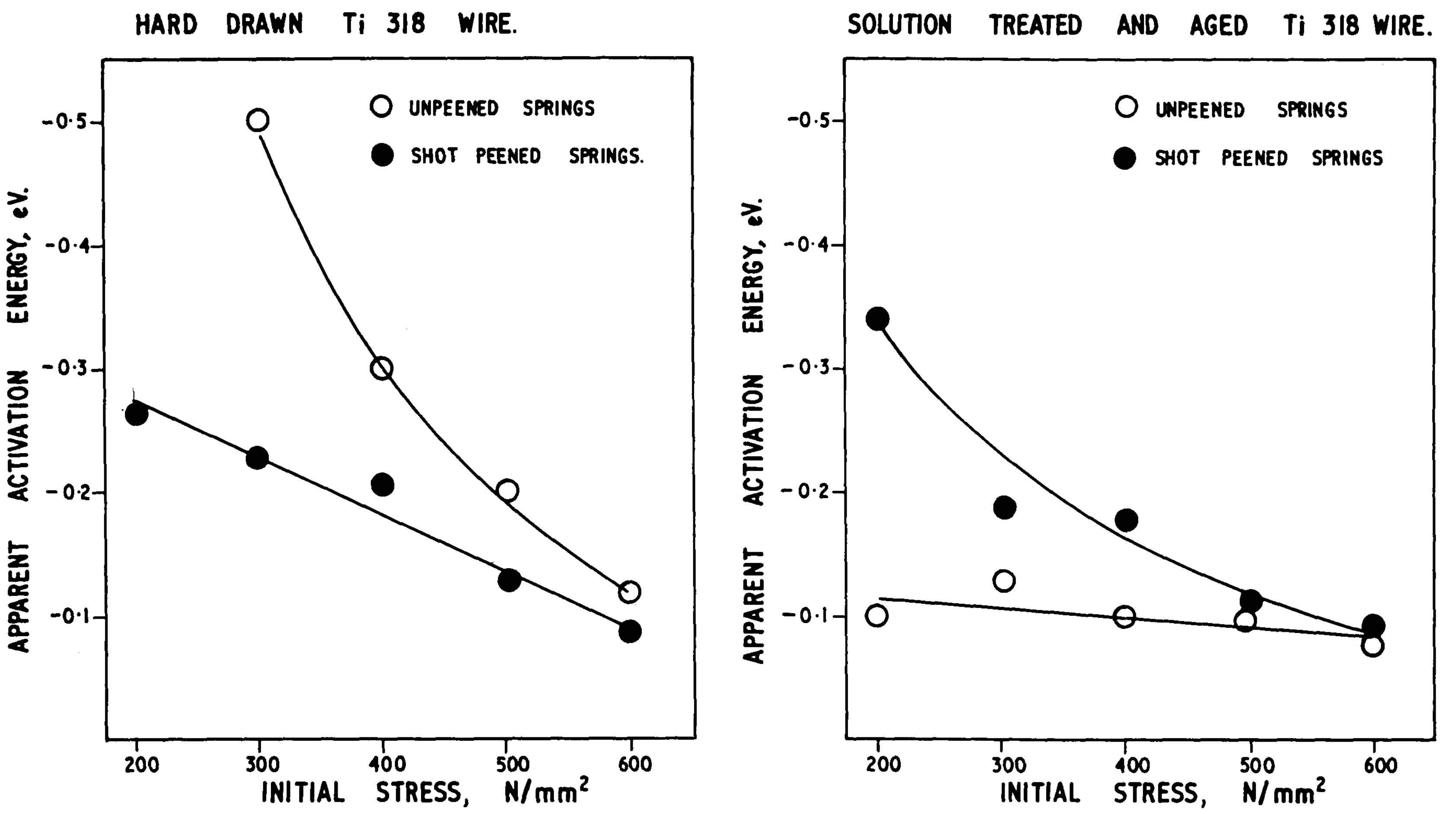

FIG. 30 APPARENT ACTIVATION ENERGY FOR STRESS – RELAXATION OF PEENED AND UNPEENED SPRINGS MANUFACTURED FROM TITANIUM 318 WIRE.