THE SPRING RESEARCH AND MANUFACTURERS' ASSOCIATION

THE FATIGUE AND RELAXATION PROPERTIES OF SHOT PEENED HELICAL COMPRESSION SPRINGS MADE FROM 527A60 CARBON-CHROMIUM WIRE

by

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

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SUMMARY

The static and dynamic properties have been determined for helical compression springs manufactured from 4 mm carbon-chromium steel wire to 527A60, BS 970 Part 5, 1972. The resulting data have been compared to the appropriate data previously obtained at SRAMA, for the comparable En47, En48A and low Cr V alloys. The work has suggested that little difference exists between the fatigue properties of 527A60, En47 and En48A compression springs. By contrast, both the dynamic relaxation at 10^7 cycles and the static stress relaxation of the 527A60 springs were significantly higher than springs made from either En47 or En48A. The stress relaxation of the 527A60 springs however, was broadly similar to that of springs made from a low Cr V alloy.

It is suggested that fatigue properties are not likely to be a major factor governing the choice of alloy for a particular application but that factors such as hardenability, relaxation properties, price and availability will exert a strong influence on alloy selection.

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1. INTRODUCTION

Previous work at SRAMA has resulted in the generation of data relating to the fatigue and relaxation properties of shot-peened helical compression springs made from typical low alloy spring steels represented by En47 (Cr/V) and En48A (Cr/Si)(1,2,3,4,5). The recent specification BS 970, Part 5, 1972, makes provision for the C/Cr alloy designated 527A60, which effectively replaces the equivalent En48 alloy. The alloy 527A60 is a close equivalent to the American SAE 5160, which is widely used in the U.S.A. for the manufacture of vehicle suspension springs. It was felt that a limited investigation should be undertaken to characterise the fatigue and relaxation properties of 527A60, in view of the possibility that this alloy could achieve some popularity within the U.K. in the future.

2. MATERIAL

2.1 Composition and Heat Treatment

Straight lengths of centreless ground 4 mm diameter annealed wire were obtained to the 527A60 composition specified in BS 970, Part 5, 1972. The actual composition of the material supplied is shown in Table I, together with the composition specified in the above standard.

Samples of the bars were selected for a preliminary study of the tempering characteristics of the steel. The samples were oil quenched from 840°C, and were then tempered for 1 hour at temperatures within the range 300-500°C, after which hardness tests were carried out using a Vickers Diamond Hardness machine.

The tempering curve derived from this study is shown in Fig. 1. This information was subsequently used to establish the appropriate conditions for the heat treatment of springs made from the 527A60 wire.

2.2 Spring Design and Manufacture

Springs were hand coiled to the design shown in Table II. The coiled springs were heat treated by normal commercial techniques to give a hardness of 470 HV ±20 HV, after which they were end ground and pre-stressed 4 times over a mandrel, trials having previously shown that the springs were generally stable after 3 pre-stressing operations. The springs were subsequently shot peened to an intensity of 0.635 mm A2 using S330 shot, and were then stress relieved at 220°C for ½ hour, after which they were given a final, single pre-stressing treatment before testing.

3. EXPERIMENTAL PROCEDURE

3.1 Mechanical Tests on Wire

Samples of the wire were heat treated at SRAMA by O.Q. from 840°C and tempering at 450°C, to give a final hardness of 465-473 HV.

Full tensile and torsional properties were then determined in triplicate using techniques which have been fully described in an earlier report(6).

The results of the tensile tests are given in Table III, whilst the torsional properties are shown in Table IV.

3.2 Microstructural Examination and Hardness Testing of Heat Treated Springs

Samples were cut from a number of the commercially heat treated springs, and were prepared for metallographic examination and hardness testing.

Microscopical examination after etching in 4% Nital revealed that the samples possessed a uniformly heat treated structure of tempered martensite, with no signs of decarburisation or excessive oxidation at the surface.

Hardness tests carried out on the samples showed the springs to possess a hardness lying within the range 444-451 HV30, which was considered acceptable for normal commercial practice.

3.3 Fatigue Testing of Springs

The fatigue tests were carried out using a forced motion multiple station machine which operated at 25 Hz. Initial stresses of 200, 150 and 70 N/mm^2 were used for the tests, the latter being the lowest values of initial stress which could be reliably used on the available machines.

The springs were load tested to determine the deflections necessary for the required minimum and maximum stresses, by use of the standard relationship

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

where P = Load, N

d = wire diameter, mm

τ = applied torsional stress, N/mm^2

D = mean coil diameter

K = Sopwith correction factor

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

where c = Spring Index = $\frac{D}{d}$

After fatigue testing, all the broken springs were closely examined to ensure that the results used for the subsequent statistical analyses were obtained from springs which had not failed prematurely due to gross surface defects, end grinding marks, etc.

The springs which survived unbroken to 10^7 cycles were removed from the fatigue machine and were then re-load tested at the original loaded length. From these results, the dynamic relaxation of the unbroken springs could be easily calculated.

3.4 Stress Relaxation Testing of Springs

Relaxation testing was carried out using the "nut and bolt" technique which has been described in detail in earlier reports, the springs having first been load tested via the technique explained in Section 3.3 of this report(7,8).

Triplicate tests were carried out at temperatures of 150, 175 and 200°C, and initial stresses of 300, 500, 700 and 900 N/mm^2, for a time of 72 hours at temperature. All the necessary measurements were made at ambient temperature and no allowance was made for the loss in load accompanying the change in rigidity modulus with temperature.

If so required, the initial stress at elevated temperature can be calculated from the expression

$$\tau_T = \tau_o \frac{G_T}{G_o} \qquad \text{..........} \quad (2)$$

where τ_T = Torsional stress at temperature T°C
τ_o = Torsional stress at ambient temperature
G_T = Rigidity modulus at temperature T°C
G_o = Rigidity modulus at ambient temperature

4 RESULTS AND DISCUSSION

4.1 Fatigue Properties

The results of the fatigue tests are shown plotted as S/N curves in Figs. 2-4. It should be noted that the regression curves representing the data at initial stresses of 70 N/mm^2 and 200 N/mm^2 were obtained by consideration of reciprocal relationships, the correlation coefficients of which were examined using the students 't' test. Both coefficients were found to be significant at the minimum acceptable level of 95%.

The data obtained at an initial stress of 150 N/mm^2 could not be adequately represented by any of the usual regression techniques applied to fatigue data, and hence the curve was fitted by eye to represent this information. In all cases, the appropriate confidence intervals were obtained by consideration of the residuals derived from the appropriate S/N curves and the associated fatigue data.

The Goodman diagram derived from the S/N curves is shown in Fig. 5.

The appropriate fatigue properties of the 527A60 springs, abstracted from the Goodman diagram, are shown in Table V together with the results of previous work carried out on similar springs made from the comparable alloys En47 and En48A(1,2,3).

The information shown in Table V would appear to suggest that the springs made from 527A60 were generally inferior in fatigue to those made from En47 and En48A of a similar wire size. This broad statement requires some qualification, however, for two main reasons.

1. The heat treated 527A60 springs exhibited a hardness of 445-451 HV, corresponding to a tensile strength of approximately 1460 N/mm^2. Springs made from the comparable alloys, however, were heat treated to give hardness and approximate tensile strength values of 500-550 HV and 1580-1790 N/mm^2 respectively. Previous work at SRAMA has indicated that an increase in tensile strength of 155 N/mm^2 can result in a corresponding increase of 20 N/mm^2 in the fatigue limit of hard drawn carbon steel compression springs(9).

2. The 527A60 springs were designed to a solid stress of 71% of the tensile strength. By contrast, the springs made from the two comparable alloys were designed to give solid stresses lying within the range 56%-76% of the tensile strength.

This difference in solid stress is significant, in that previous work at SRAMA has indicated that higher solid stresses in compression springs were associated with superior fatigue properties(10). In this same work, however, a technique was developed for the derivation of fatigue data at any solid stress, given the actual data obtained for a particular value of this parameter. It was shown that for a particular number of cycles of fatigue, the relationship between the solid stress, the initial stress and the final (maximum) stress could be represented by the linear expression

$$(SS - IS) = A\ (SS - FS) + B \qquad \text{..........(3)}$$

where SS = Solid stress, N/mm^2
IS = Initial stress, N/mm^2
FS = Final stress, N/mm^2
A = Slope of the regression curve of (SS - IS)/(SS - FS)
B = Constant of proportionality

Hence, for a given solid stress and fatigue life, this relationship can be established for the values of FS and IS obtained from the experimentally determined Goodman diagram. Further Goodman diagrams can then be constructed for selected values of solid stress by transposition,

$$FS = SS - \frac{(SS - IS) - B}{A} \qquad \text{..........(4)}$$

This technique was used to correct the available fatigue data for En47 and En48A to the solid stress of 1030 N/mm^2 used in the present investigation. The resulting information is shown in Tables VI and VII, both of which also display the Fatigue Ratio, which is here understood to mean the (Fatigue Strength at Zero Initial Stress/Tensile Strength) for a given number of cycles of operation. The information is presented in the form of Goodman diagrams in Figs. 6 and 7. It should be noted that there was no difference of any statistical significance between the data depicting the fatigue limit at 10^7 cycles for En47 and En48A springs, and these data have therefore been combined in the 99% confidence band shown in Fig. 7, for the sake of clarity.

It can be seen from these results that, in terms of the appropriate Fatigue Ratios, the 527A60 springs exhibited a fatigue performance which was broadly similar to that of the other two comparable low alloy spring materials, for both the limited and the unlimited life data. This would appear to suggest that the heat treated condition of this group of alloys is one of the main factors governing the fatigue performance, higher tensile properties and higher hardness levels being associated with higher fatigue strengths under equivalent fatigue conditions, thus confirming the findings of the earlier work at SRAMA(9).

4.2 Dynamic Relaxation Properties

The values of dynamic relaxation, recorded for those springs unbroken after 10^7 cycles, are shown in Table VIII.

These data can be compared with those obtained in previous work at SRAMA on En47 springs, where springs unbroken after 10^7 cycles experienced a mean dynamic relaxation of 2.8% at an initial stress of 300 N/mm^2(3).

In the present case, the trend of increasing dynamic relaxation with increasing initial stress shows that the 527A60 springs exhibited approximately 3.4% dynamic relaxation at an initial stress of 200 N/mm^2. Extrapolation of the trend indicates that the 527A60 springs would typically have experienced dynamic relaxations of the order of 5% at an initial stress of 300 N/mm^2.

These findings therefore suggest that the 527A60 springs exhibited dynamic relaxations which were approximately twice those obtained for En47 springs under similar operating conditions. It should be noted, however, that the 527A60 springs had been heat treated to a tensile strength which was approximately 300 N/mm^2 lower than that of the En47 springs, and hence some improvement may be obtained by raising the tensile strength to the appropriate level.

4.3 Stress Relaxation Properties

The relaxation results obtained during the present work were found to be adequately represented by exponential relationships which have been previously used at SRAMA to describe the relaxation behaviour of several spring materials(11,12).

The exponential relationship takes the general form

$$\text{Rel} = \alpha e^{\beta \tau} \qquad \text{..........(5)}$$

where Rel = % Relaxation

τ = Maximum initial torsional stress, N/mm^2

α and β are constants at a particular test temperature

The regression coefficients obtained for the plots ln Rel/τ were all significant at the 99.9% level of the 't' distribution. Analysis of the residuals obtained from the 50% regression curves, shown in Fig. 8, suggests that the 99% confidence levels of the appropriate curves would be as follows:

Relaxation Temperature	99% Confidence Band
150°C	±2.1% Relaxation
175°C	±0.9% "
200°C	±2.4% "

These levels of experimental scatter are in good agreement with those obtained during previous work at SRAMA(11,12).

The stress relaxation properties of springs manufactured from shot peened 527A60, En47 and a low Cr/V steel are shown together for comparison in Table IX(4,5,13).

The available data are plotted in Fig. 9, which summarises the stress-relaxation results obtained at 150°C for the four alloys considered.

Whilst it is only possible to draw general conclusions from this limited information, it is clear that the 527A60 springs exhibited levels of stress relaxation which were significantly higher than those obtained for En47 and En48A springs. The stress relaxation properties of the 527A60 and the low Cr V springs, however, were very similar at 150°C over the range of initial stresses investigated.

It must be remembered that the 527A60 springs used in the present work were heat treated to produce tensile strengths which were approximately 300 N/mm^2 lower than the other three alloys, and 527A60 may therefore show some improvement if heat treated to hardness levels within the range 500-550 HV.

In general, however, it can be concluded that the 527A60 springs tested in the present instance exhibited levels of stress relaxation which were approximately twice those of En47 springs and five times those of En48A springs, tested under similar conditions, a conclusion which was broadly supported by the dynamic relaxation behaviour reported in Section 4.2. Based on the results of earlier work at SRAMA, however, it is possible that hot pre-stressing of shot peened 527A60 springs could provide significant reductions in the relaxation levels encountered during the course of the present work (4,5).

Further work in this direction may therefore be considered desirable in the future.

4.4 Temperature Dependence of Stress Relaxation

Following recent work at SRAMA, the relaxation of spring materials has been shown to be related exponentially to the reciprocal of the Absolute Temperature via a relationship of the general form (11,12,14,15).

$$\text{Rel} = \gamma e^{\frac{-\delta}{T}} \qquad \text{..........(6)}$$

where Rel = % Relaxation after a stipulated time
T = Relaxation temperature, °K
γ and δ are constants at a particular level of initial applied stress, τ N/mm^2

This relationship can be derived directly from the experimental results, since by taking logarithms

$$\ln(\mathrm{Rel}) = -\frac{\delta}{T} + \ln\gamma \qquad \text{..........(7)}$$

Hence regression analysis of $\ln(\mathrm{Rel})/\frac{1}{T}$ yields the corresponding values of the constants δ and γ.

The relationships given in Equations 5 and 6 are useful in that they permit interpolation for relaxation at temperatures and stresses between those employed during the investigations.

The appropriate values for the constants α, β, γ and δ are given in Tables X and XI.

The apparent thermal activation energy for relaxation can be determined from the appropriate values of δ, since

$$\delta = \text{Slope of } \ln(\mathrm{Rel})/\frac{1}{T}\ {}^{\circ}\mathrm{K} \text{ plot}$$
$$= -\frac{Q}{R}$$

where Q = Apparent thermal activation energy for relaxation, $\mathrm{J.mol^{-1}}$

R = Universal Gas Constant

= $8.36\ \mathrm{J.mol^{-1}\ {}^{\circ}K^{-1}}$

(Note: 1eV = $96300\ \mathrm{J.mol^{-1}}$)

The values of Q thus derived are shown against initial torsional stress in Fig. 10. These results show that Q decreases as the initial applied stress increases, a feature common to other work carried out at SRAMA on the stress-relaxation of carbon steel strip and of both Ti318 and phosphor-bronze alloy compression springs(11,12,13).

Furthermore, it is of some interest that the previous work on martensitic carbon steel strip, which was carried out in 4-point bending, gave values of Q which are very similar to those obtained for the present work on martensitic 527A60 helical compression springs, which operate largely in torsion. This could be interpreted as suggesting that a basic similarity exists in the physical metallurgy of the relaxation processes, occurring during both bending and torsion.

Thus the results of relaxation work upon springs operating in bending may be broadly applicable to those of the same materials operating in torsion, and vice versa. Further work would be necessary to substantiate or disprove this tentative suggestion however.

5. CONCLUSION

1. The work has suggested that, at equivalent tensile strengths and solid stresses, both the limited and the unlimited life fatigue properties of 527A60, En47 and En48A springs are very similar. This would suggest that the fatigue performance of these alloys is dependent upon the heat treated condition rather than upon the chemical composition of the steel.

2. 527A60 springs exhibit levels of dynamic relaxation, at 10^7 cycles, which are approximately twice those of En47 springs under equivalent test conditions.

3. At equivalent temperatures and initial stresses, 527A60 springs exhibit levels of stress relaxation which are approximately twice those of En47 springs, and five times those of En48A springs. The springs made from low Cr V however, possessed stress relaxation properties which were very similar to those of the 527A60 springs.

4. The above results would suggest that, for a particular application, the choice of alloy will tend to be dictated by the hardenability and stress relaxation properties, together with price and availability, rather than by the difference in fatigue properties.

6. RECOMMENDATIONS

1. It would be desirable for completeness to carry out fatigue and relaxation tests on similar 527A60 springs of appropriate design, heat treated to a hardness ~~of~~ 550 HV.

2. Work should be undertaken to investigate the effects of hot prestressing upon the stress relaxation behaviour of

527A60 springs. Previous work at SRAMA has shown that the use of this process can lead to significant improvements in relaxation behaviour.

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TABLE I CHEMICAL COMPOSITION OF 527A60 BAR MATERIAL

Chemical Analysis	Element, wt %							
	C	Si	Mn	Cr	S	P	Mo	Ni
BS 970 1972 Part 5	0.55 -0.65	0.1 -0.35	0.7 -1.00	0.6 -0.9				
Actual	0.61	0.34	0.87	0.78	0.027	0.009	0.02	0.13

TABLE II SPRING DESIGN

Wire diameter, mm	4
Mean coil diameter, mm	30
Total coils	5.6
Active coils	3.6
Free length, mm	55
Measured solid stress, N/mm^2	1030

TABLE III TENSILE PROPERTIES OF 4 mm DIAMETER 527A60 WIRE HEAT TREATED TO 470 HV

Sample Number	Tensile Parameter						
	R_m N/mm^2	L of P N/mm^2	R_p 0.05 N/mm^2	R_p 0.1 N/mm^2	R_p 0.2 N/mm^2	R of A N/mm^2	Elongation on 50 mm %
1	1460	660	1200	1230	1250	41	5
2	1460	660	1210	1230	1240	41	5
3	1450	670	1200	1220	1230	40	6
Mean Value	1460	660	1200	1230	1240	41	5

TABLE IV TORSIONAL PROPERTIES OF 4 mm DIAMETER 527A60 WIRE HEAT TREATED TO 470 HV

Sample Number	Torsional Parameter					
	L of P N/mm^2	0.05% PS N/mm^2	0.1% PS N/mm^2	0.2% PS N/mm^2	0.5% PS N/mm^2	G N/mm^2
1	610	790	830	880	930	7.53×10^4
2	660	780	810	860	940	7.5×10^4
3	730	800	840	890	910	7.51×10^4
Mean Value	670	790	830	880	930	7.51×10^4

TABLE V FATIGUE STRENGTH OF SHOT PEENED COMPRESSION SPRINGS MADE FROM 527A60 AND COMPARABLE MATERIALS

Material	Wire dia. mm	R_m N/mm^2	Solid stress N/mm^2	No of Cycles N	Fatigue Parameter	Fatigue strength, N/mm^2 at Initial stress, N/mm^2		
						70	150	200
527A60	4	1460	1030	10^5	99% C.L.	830	900	950
En47(3)	4	∿1620	1160	"	"	1020	1060	1090
527A60	4	1460	1030	10^7	Fatigue Limit	700	800	850
En47(1)	3.25	1580	1200	"	"	890	930	960
En48A(1)	3.25	1790	1200	"	"	870	920	950
En48A(2)	4.2	1700	950	"	"	780	840	880

TABLE VI FATIGUE STRENGTH AT 10^5 CYCLES AND 99% CONFIDENCE FOR SHOT PEENED COMPRESSION SPRINGS OF 527A60 AND En47, CORRECTED TO A COMMON SOLID STRESS OF 1030 N/mm^2

Material	Wire dia. mm	R_m N/mm^2	Fatigue strength, N/mm^2 at Initial stress, N/mm^2				Fatigue Ratio
			0	70	150	200	
527A60	4	1460	770	830	900	950	0.53
En47(3)	4	∿1620	920	960	1000	-	0.57

TABLE VII FATIGUE STRENGTH AT 10^7 CYCLES (FATIGUE LIMIT) FOR SHOT PEENED COMPRESSION SPRINGS OF 527A60 AND COMPARABLE ALLOYS, CORRECTED TO A COMMON SOLID STRESS OF 1030 N/mm^2

Material	Wire dia. mm	R_m N/mm^2	Fatigue limit, N/mm^2 at Initial stress, N/mm^2				Fatigue Ratio
			0	70	150	200	
527A60	4	1460	640	710	790	840	0.44
En47(1)	3.25	1580	780	815	860	885	0.49
En48A(1)	3.25	1790	765	810	860	895	0.43
En48A(2)	4.2	1700	740	795	860	900	0.44

TABLE VIII DYNAMIC RELAXATION RESULTS FOR 527A60 SPRINGS UNBROKEN AFTER 10^7 CYCLES

Initial stress N/mm^2	Maximum stress N/mm^2	Life cycles x 10^7	Dynamic Relaxation %
70	700	1.0485	1.6
"	750	1.0431	1.0
"	750	1.0485	3.9
150	600	1.4506	0
"	650	1.287	-0.6
"	700	1.4506	1.6
"	750	1.287	0.3
"	800	1.323	3.4
"	850	1.026	5.3
"	850	1.0485	4.3
200	750	1.026	2.1
"	800	1.026	3.4
"	825	1.0431	4.0
"	850	1.026	4.1
"	850	1.0323	2.6
"	875	1.0512	5.9
"	875	1.0431	4.8

TABLE IX STRESS RELAXATION OF SHOT PEENED HELICAL COMPRESSION SPRINGS MADE FROM 527A60 AND COMPARABLE LOW ALLOY STEELS

Relaxation conditions:- 150°C/ 72 hrs
Initial stress, 800 N/mm^2

Material	Wire dia. mm	Hardness HV	Solid stress N/mm^2	Relaxation % (Rounded)
527A60	4	470±20	1030	15
Low Cr V (13)	2.5	500-550	1245	12
En47 (4)	3.8	500	1300	9
En48A (4)	3.8	560	1300	3

TABLE X VALUES OF EMPIRICAL CONSTANTS FOR EXPONENTIAL STRESS-RELAXATION/STRESS RELATIONSHIPS

Relaxation temperature °C	Constants for Rel = $\alpha e^{\beta\tau}$	
	α	$\beta \times 10^{-3}$
150	1.0304	3.3062
175	1.6624	2.9207
200	3.1038	2.2574

TABLE XI VALUES OF EMPIRICAL CONSTANTS FOR EXPONENTIAL STRESS-RELAXATION/ABSOLUTE TEMPERATURE RELATIONSHIPS

Initial stress N/mm^2	Constants for Rel = $\gamma e^{-\delta/T}$	
	γ	δ
300	11122.2	-3541.49
500	419.36	-1807.84
700	225.78	-1296.61
900	179.01	-930.66

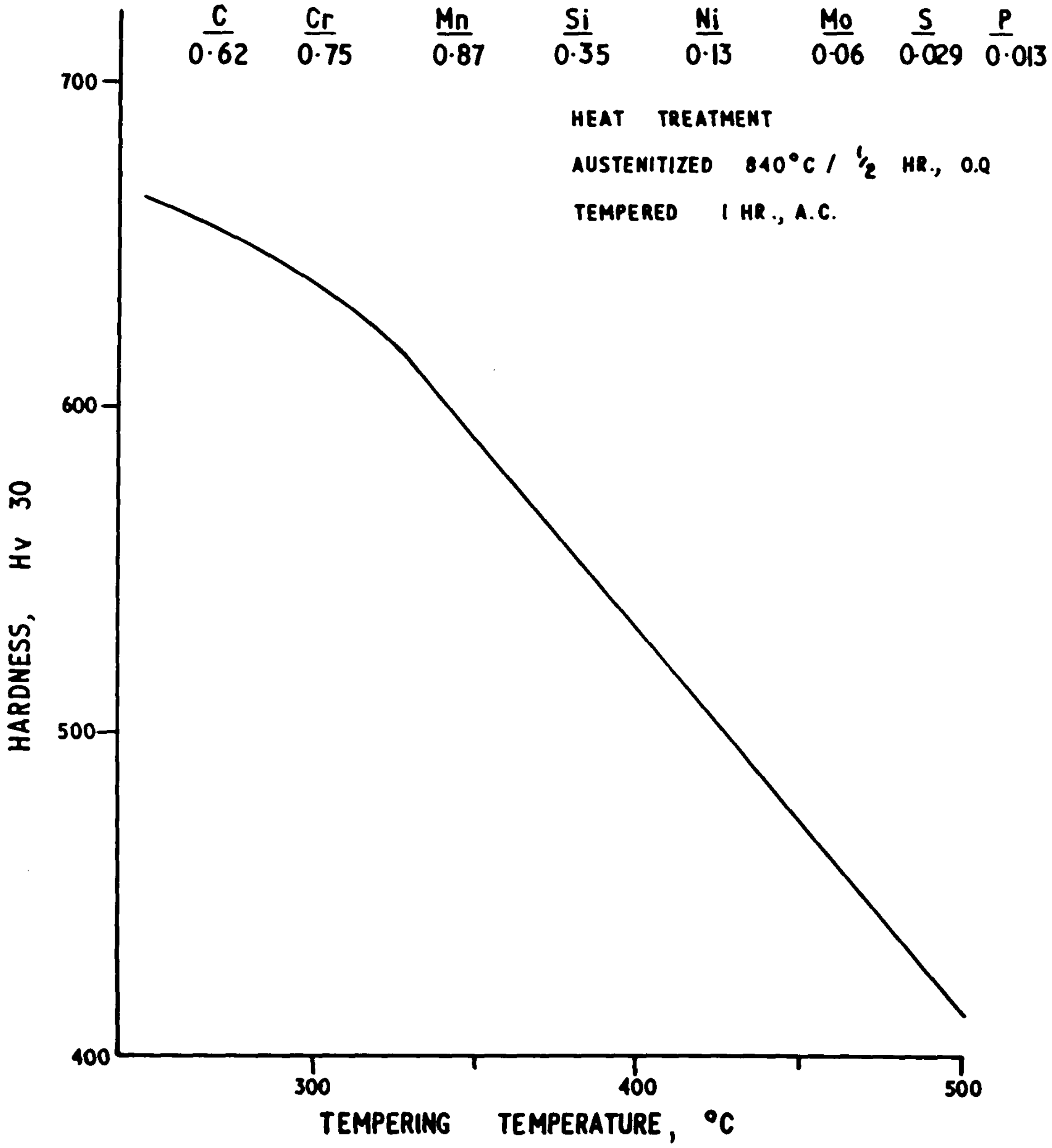

FIG. 1 TEMPERING CURVE FOR HARDENED 527A60 STEEL.

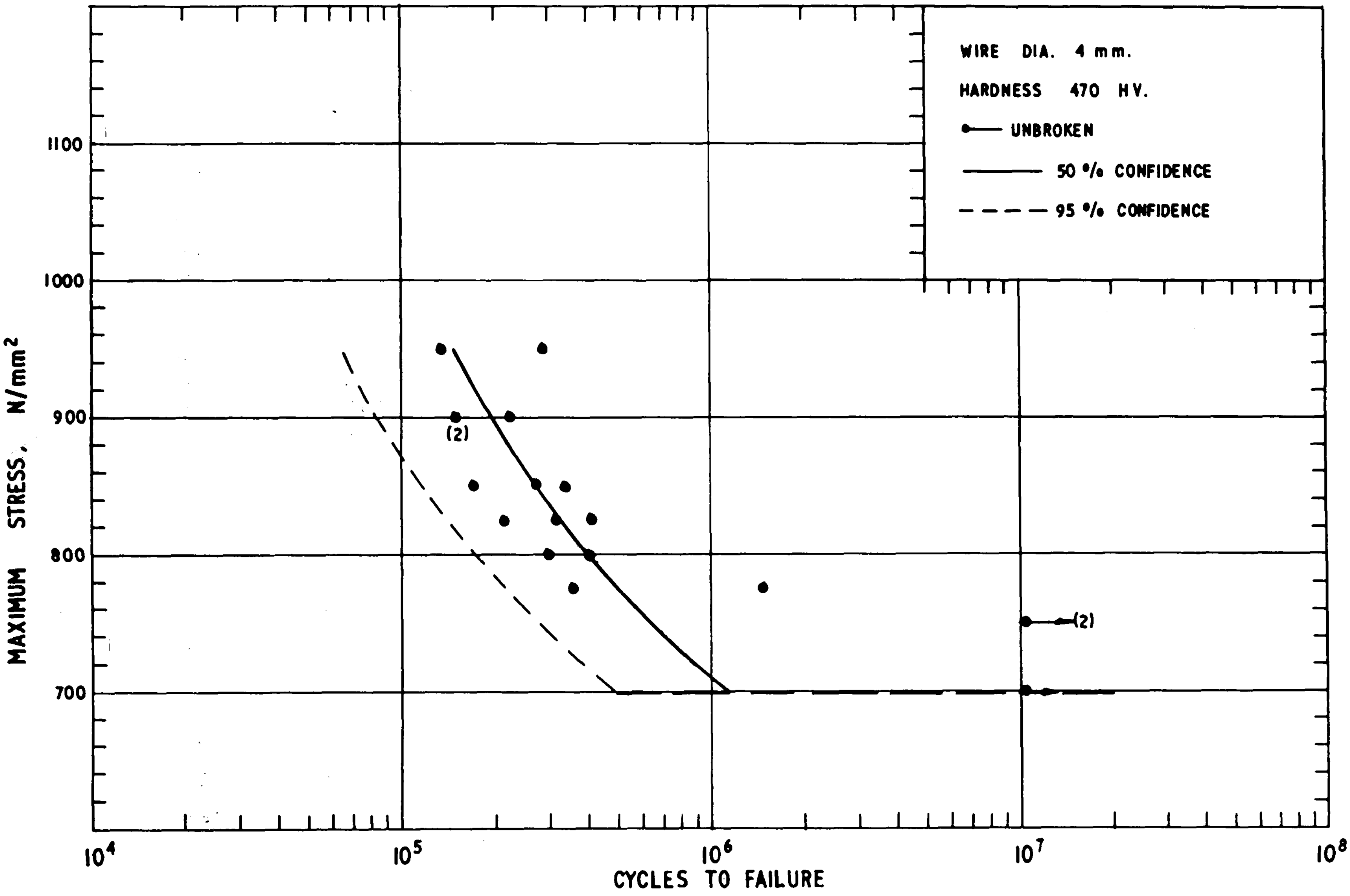

FIG. 2 S/N CURVE FOR SHOT PEENED SPRINGS OF 527 A60 AT INITIAL STRESS 70 N/mm^2

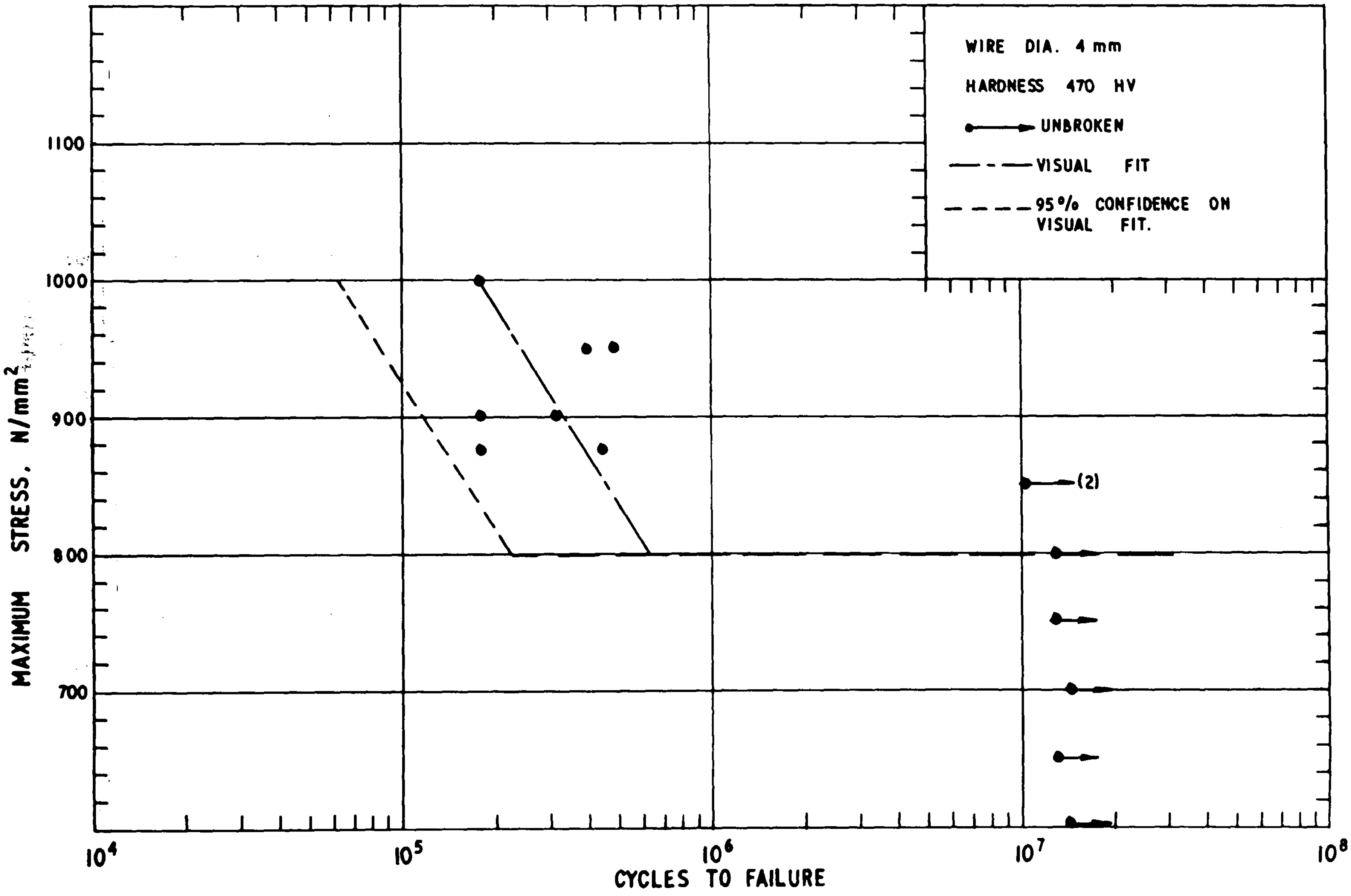

FIG. 3 S/N CURVE FOR SHOT PEENED SPRINGS OF 527 A60 AT INITIAL STRESS 150 N/mm²

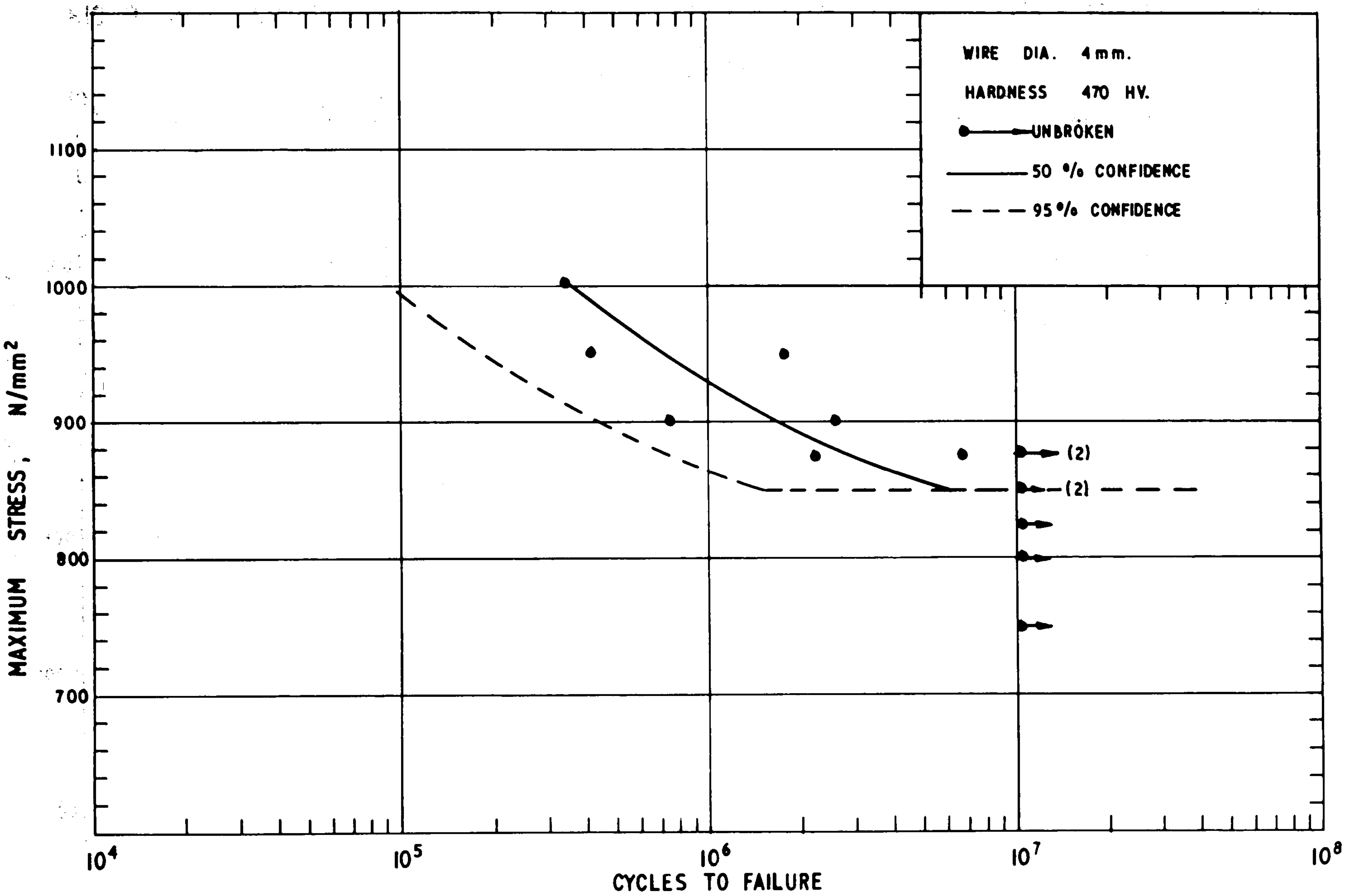

FIG. 4 S/N CURVE FOR SHOT PEENED SPRINGS OF 527 A60 AT INITIAL STRESS 200 N/mm²

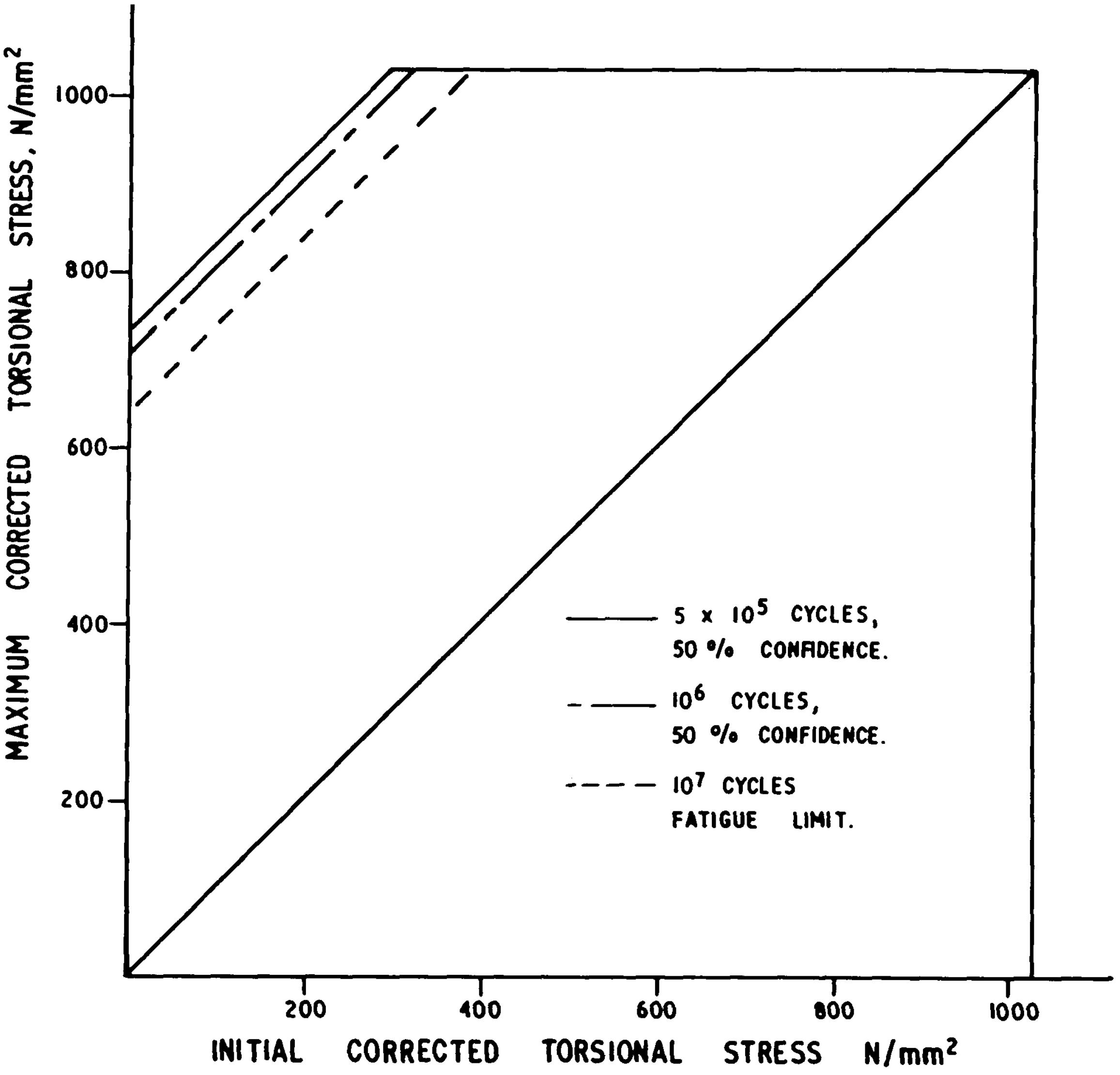

FIG. 5 MODIFIED GOODMAN DIAGRAM FOR SHOT PEENED SPRINGS MANUFACTURED FROM 4 mm. DIA. 527 A60 WIRE TO SOLID STRESS OF 1030 N/mm^2

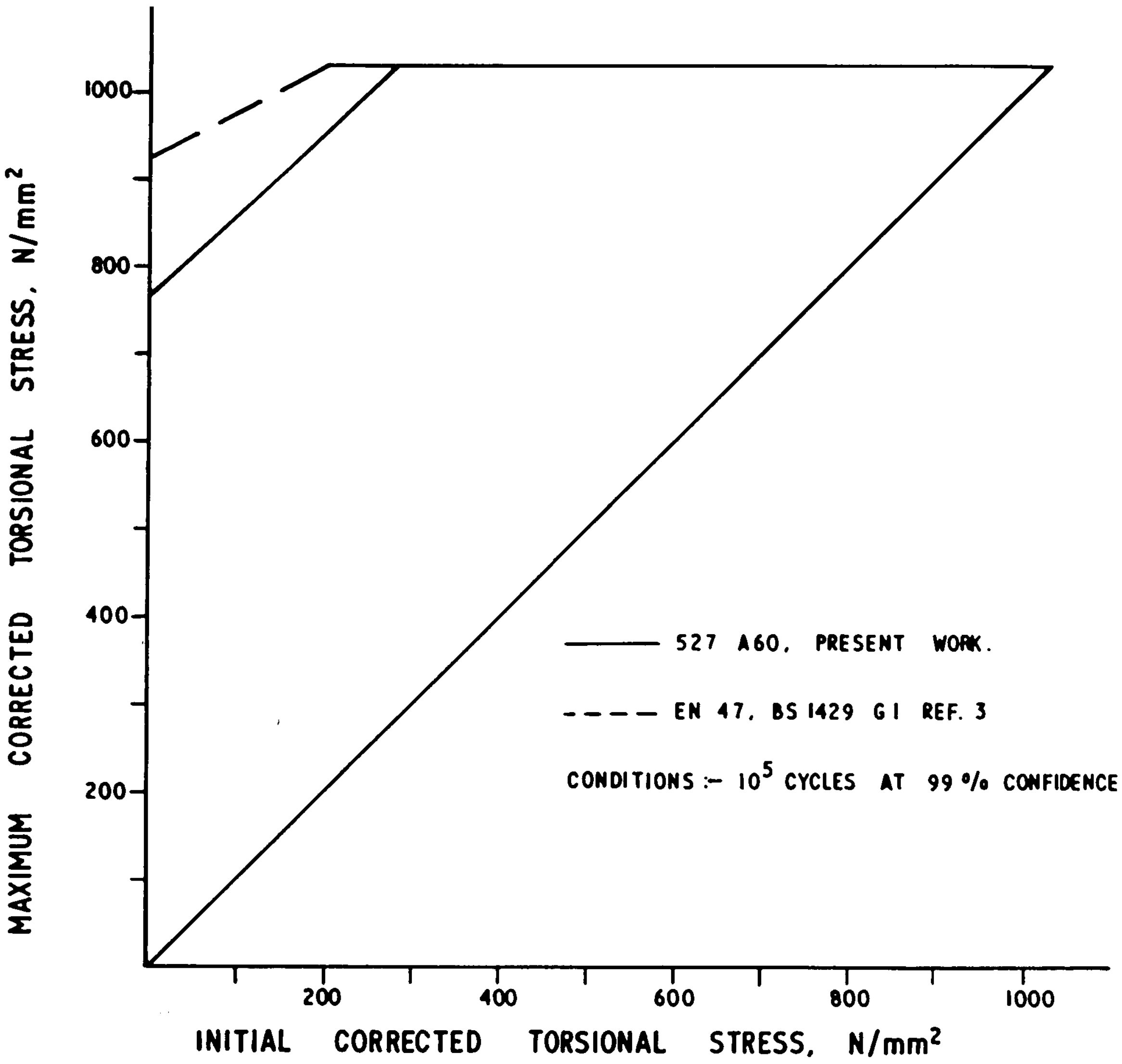

FIG. 6 MODIFIED GOODMAN DIAGRAM AT 10^5 CYCLES FOR SHOT PEENED SPRINGS DESIGNED TO SOLID STRESS OF 1030 N/mm²

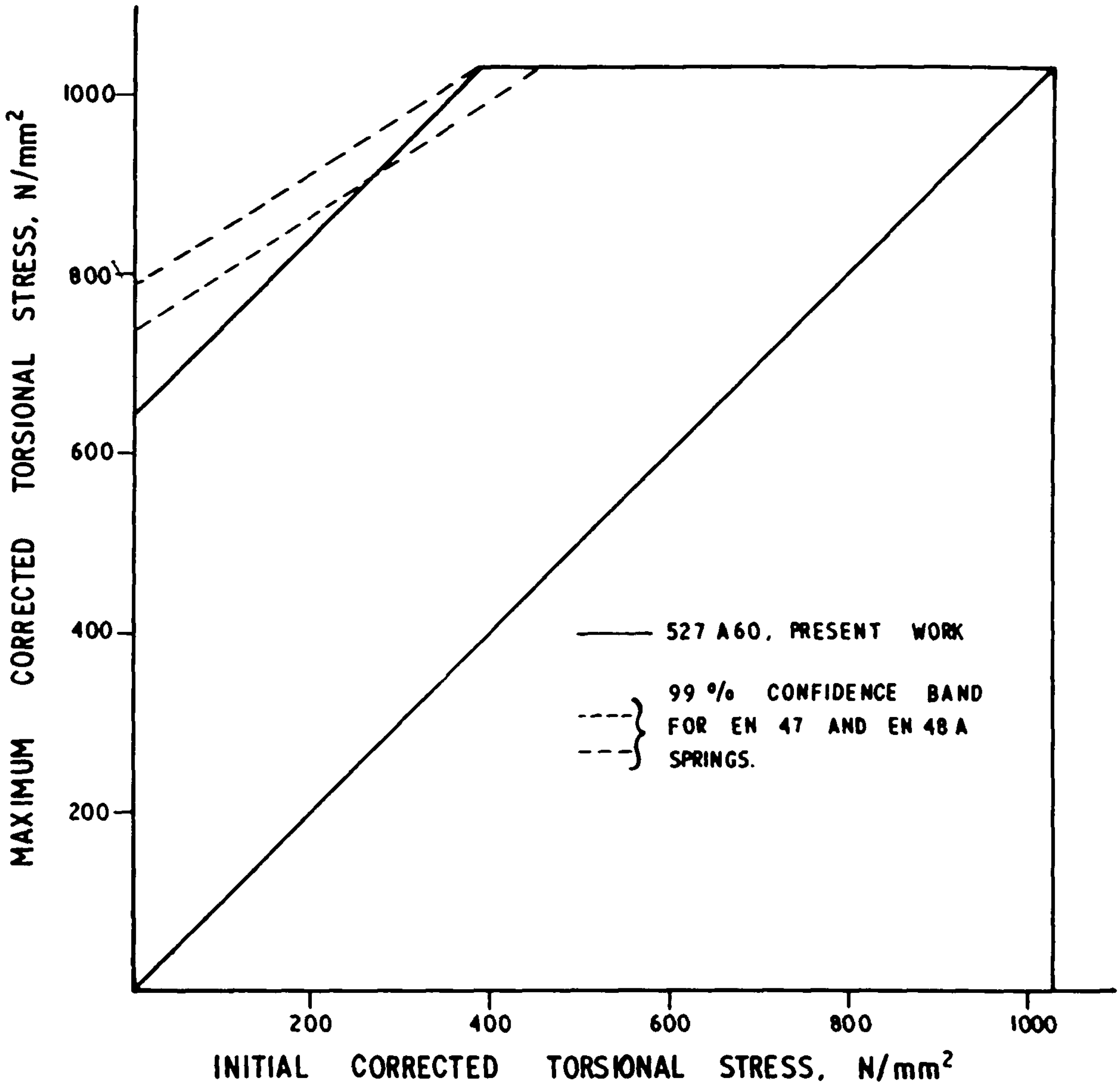

FIG. 7 MODIFIED GOODMAN DIAGRAM AT 10^7 CYCLES FOR SHOT PEENED SPRINGS DESIGNED TO SOLID STRESS OF 1030 N/mm²

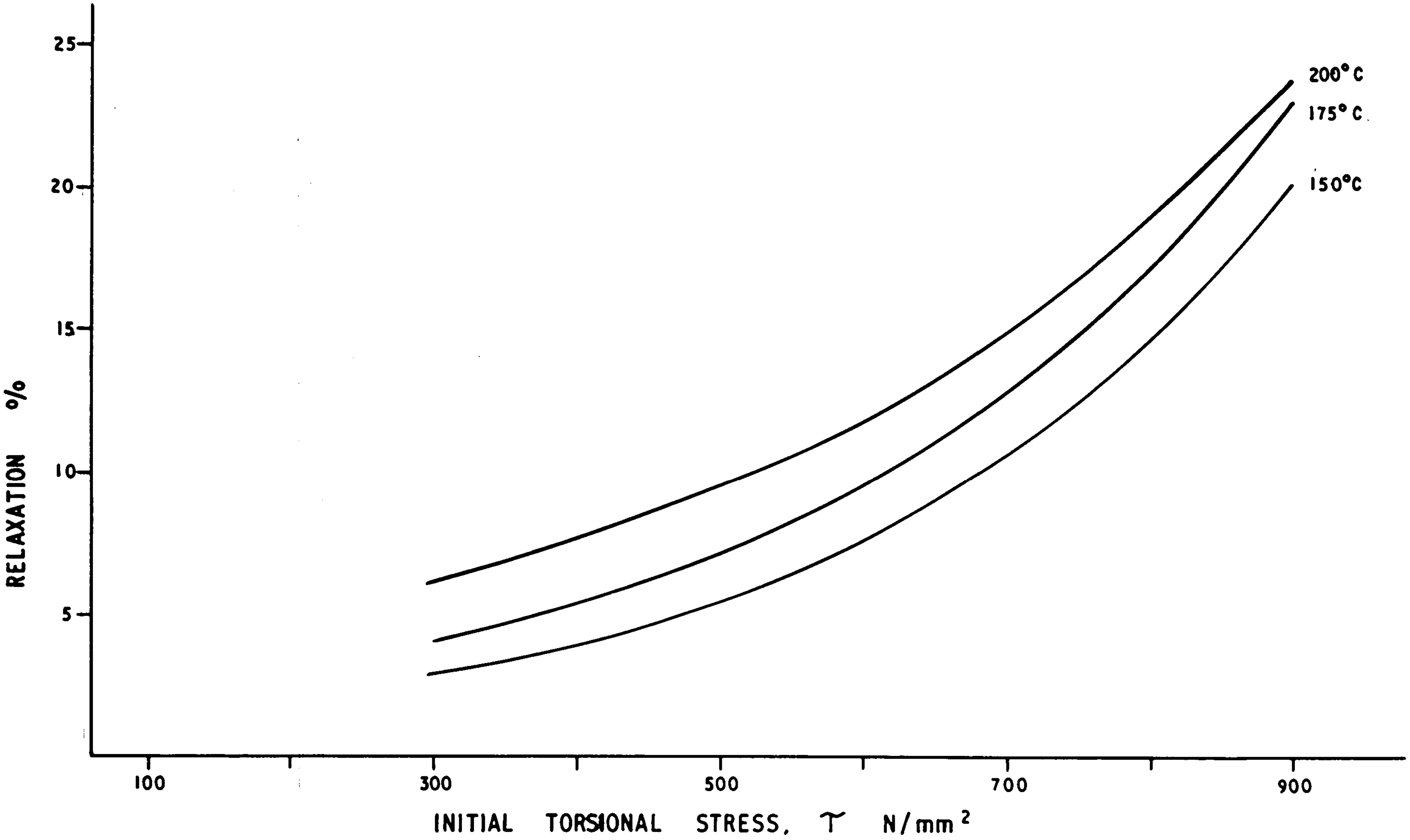

FIG. 8 STRESS RELAXATION OF SHOT PEENED SPRINGS MADE FROM 527 A60 STEEL.

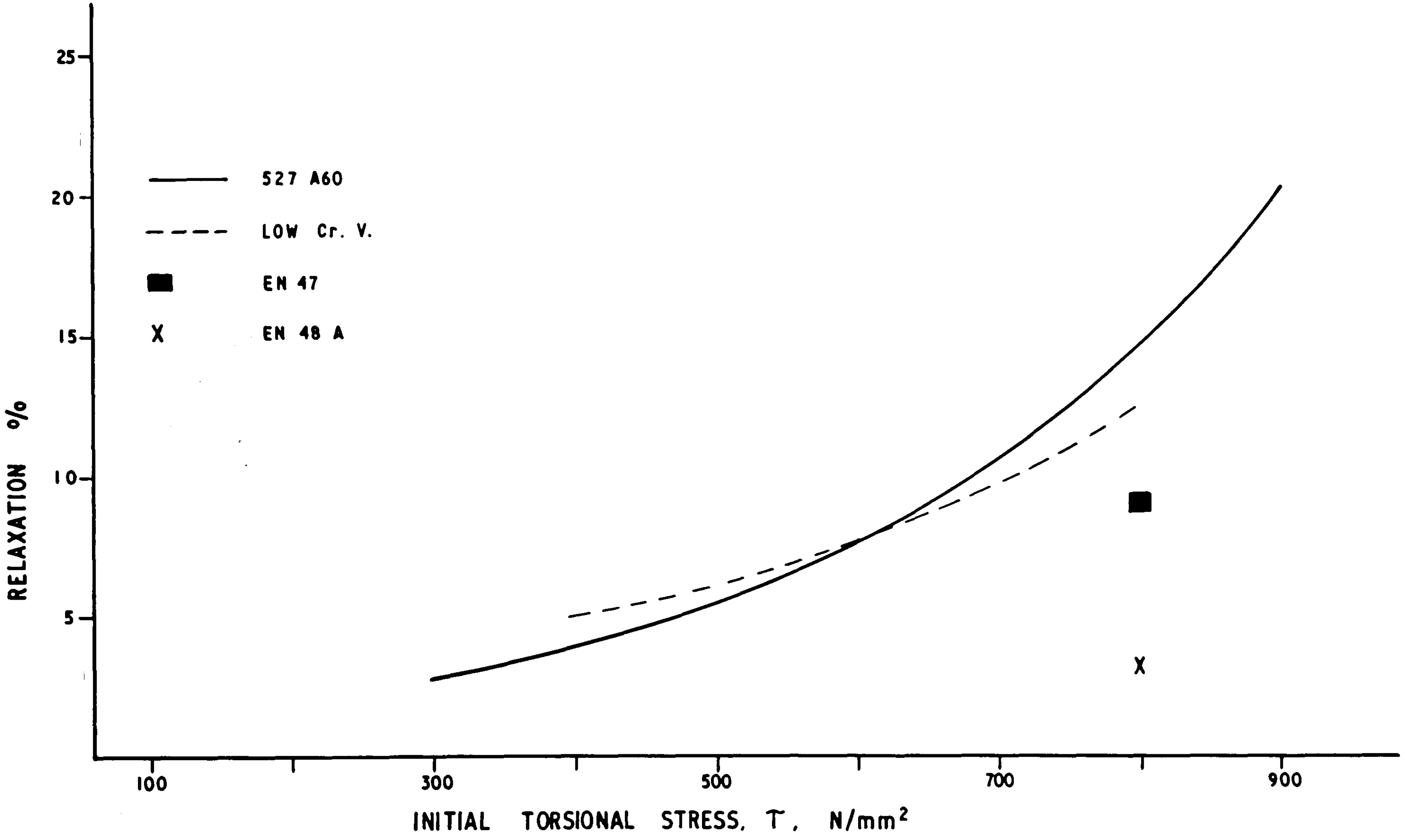

FIG. 9 STRESS RELAXATION AT 150°C OF SHOT PEENED SPRINGS MADE FROM 527 A60 AND COMPARABLE STEELS.

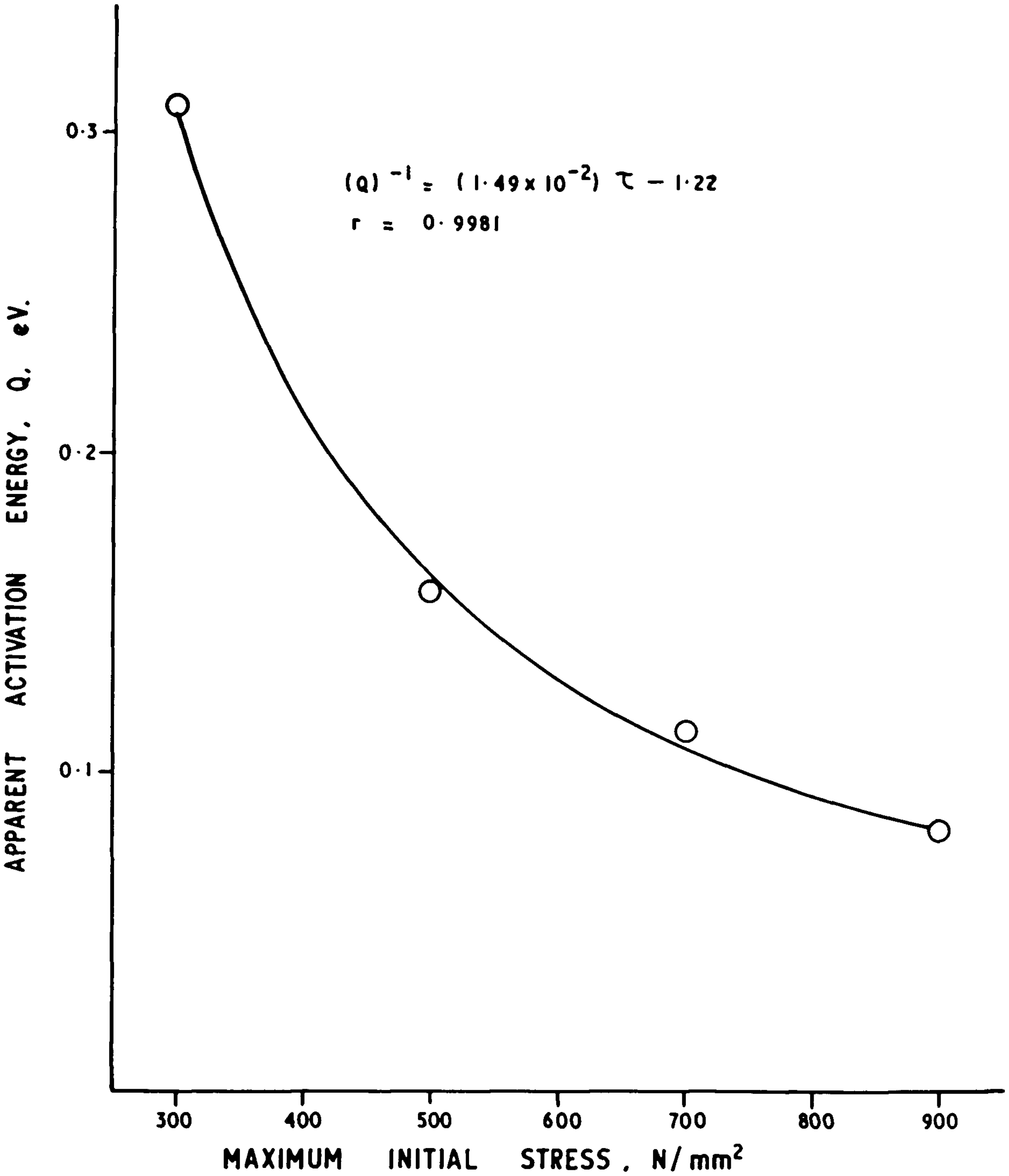

FIG. 10 VARIATION OF APPARENT THERMAL ACTIVATION ENERGY FOR RELAXATION WITH APPLIED INITIAL STRESS FOR SHOT PEENED SPRINGS MADE FROM 527 A 60 STEEL.