THE SPRING RESEARCH ASSOCIATION

THE EFFECT OF STRAIN PEENING ON THE FATIGUE PROPERTIES OF FLAT SPRINGS.

by

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Report No. 247

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SUMMARY

It has been demonstrated that the fatigue performance in bending obtainable from flat springs made from hardened and tempered CS 80 material can be substantially improved by strain peening. The fatigue limit after strain peening is at least twice that resulting from shot peening alone. It is probable that the allowable stress for a particular limited life is increased by a similar proportion. This improvement is thought to be due to increases in both the magnitude and the depth of the induced residual compressive stress.

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1. INTRODUCTION

Strain peening is a process which involves the shot peening of material while it is in a state of stress. It has been known for several years that strain peening can result in better fatigue performance than shot peening alone,(1, 2) provided that certain conditions are fulfilled. The process is only of advantage for components which are subjected to unidirectional repeat loading, and during shot peening the strain must be applied in the direction in which the component is to be used in service. The technique has in the past been applied with some success to leaf springs(3) but only a limited amount of quantitative information has been published concerning the improvements in fatigue properties. More recently, confidential work at SRA has demonstrated that strain peening can markedly extend the fatigue life of leaf springs.

The present work was undertaken to examine and, if possible, to quantify, the effects of strain peening, under known and controlled stress conditions, on the fatigue performance of hardened and tempered carbon steel strip having a thickness of 2.5 mm. The material chosen is one commonly used in the spring industry, both in terms of size and composition. For the purpose of comparison, fatigue data have also been obtained for strip specimens in the shot peened condition.

A theoretical consideration of the effects of strain peening on the magnitude of the residual stress in a strip which is stressed in uniaxial tension is presented by Almen.(1) Since residual stresses are elastic in nature, the maximum attainable residual stress in any material is equal in magnitude to the elastic limit of the material. Hence, for a strip stressed in uniaxial tension, the maximum residual stress which can be achieved is equal to the tensile elastic limit. Stresses which have a magnitude greater than the tensile elastic limit of the material are partially relieved by plastic deformation so that the resulting residual stress is equal to the tensile elastic limit. It is concluded by Almen that for a strip specimen stressed in uniaxial tension, the maximum residual stress is obtained by strain peening when the applied tensile stress is equal to half the tensile yield stress. In practice, however, it seems possible that some benefit may accrue from strain peening at stresses in excess of the elastic limit, since an additional beneficial effect is induced by prestressing; if the elastic limit is raised, then the maximum residual stress attainable is also raised. For the purposes of this investigation, it was therefore decided that strain peening be carried out at a stress equal to the tensile elastic limit of the material.

Investigation of the effects of strain peening will later be extended to helical compression springs made from 2.5 mm diameter pre-hardened and tempered carbon steel wire.

2. MATERIAL

2.1 Composition

A suitable quantity of CS 80 strip manufactured to BS 1449 Part 3B:1964, was purchased in the cold-rolled condition. The actual composition is given in Table I, together with the nominal composition of this grade. A transverse micro-section was polished and etched to ensure that the strip as-supplied was free from decarburisation - this proved to be the case.

2.2 Specimen Preparation

The strip was roller-straightened and specimens were manufactured as described below.

2.2.1 Tensile Specimens

Three specimens suitable for tensile testing were produced in accordance with the recommendations made in BS 18: Part 2, 1971. These had a gauge length diameter of 12.7 mm and an overall length of 307 mm.

2.2.2 Fatigue Specimens

Forty specimens suitable for bend testing on an Avery 7303 fatigue testing machine were machined from the strip. Specimen details are given in Fig. 1.

2.3 Heat Treatment

Preliminary tests were carried out to determine the heat treatment conditions necessary to produce a hardness of 500 to 510 HV in this material. This hardness is typical of that employed when CS 80 strip is used commercially for the production of flat springs. The tensile and the fatigue test specimens were oil quenched from 880°C and tempered in clamps for one hour at 385°C.

2.4 Shot Peening

This was carried out in a Tilghman's 'Tumblast' WTBOA machine using conventional CS 330 shot. The position and intensity of the blast pattern were first determined by peening a stationary flat steel plate which had been coated with a dye and which was positioned horizontally across the peening cabinet. The position of the blast pattern was shown by discoloration of the plate and also by the presence of a 'hot spot' on the plate at the centre of the pattern. The intensity was determined by placing a row of Almen blocks on the plate at the centre of the pattern and peening for various lengths of time. It was found that 45 seconds' exposure produced an arc rise of 0.46 to 0.56 mm over an elliptical area having a major axis of approximately 254 mm and a minor axis of 120 mm. The coverage was 100%.

Ten fatigue test specimens were fixed to a specially prepared support plate approximately 250 mm long and the assembly was then placed in the peening cabinet on the horizontal plate in the position determined above. The specimens were peened without rotation for 45 seconds. The same procedure was carried out for a second batch of ten specimens.

3. EXPERIMENTAL PROCEDURE

3.1 Tensile Testing

In order to select an appropriate stress level for strain peening, it was necessary to establish a tensile stress/strain curve for this material. Tensile testing was carried out using an Amsler multi-range tensile testing machine equipped with an automatic stress/strain recorder. The latter was used in conjunction with a separable extensometer having a gauge length of 50.0 mm. In all, three specimens were tested and the results, which are mean values, are given in Table II.

3.2 Strain Peening

For reasons outlined previously in the introduction, it was decided that strain peening would be carried out at a stress approximating to the tensile yield stress of the material. Since, in service, flat springs are normally subjected to uniaxial stresses only, it was possible to determine the stress for strain peening directly from the tensile stress/strain curve. The radius through which each specimen was to be bent in order to attain this stress was calculated using the standard bending formula:-

$$\frac{f}{y} = \frac{E}{R}$$

where f = bending stress
y = half of the strip thickness $(\frac{b}{2})$
E = Young's Modulus
R = radius of curvature

In this case, a radius of curvature of 200 mm was required to produce a bending stress of 1310 N/mm^2. Ten blocks, each of which was capable of supporting one specimen, were machined so that the upper face of each block had a radius of curvature of 200 mm. Four Allen screws were used to clamp one strip specimen to the curved face of each block. The ten blocks were placed in line on the horizontal plate in the shot peening cabinet and their position was adjusted so they were in the centre of the blast pattern. They were shot peened for 45 seconds to achieve an Almen arc rise of 0.46 to 0.56 mm on the face which had been strained in tension. The procedure was repeated on a further ten specimens.

3.3 Fatigue Testing

3.3.1 Standard Specimens

Two Avery 7303 fatigue testing machines, each capable of a maximum bending moment of 28.3 Nm, were used for the unidirectional bend-fatigue tests. This maximum bending moment corresponded to a maximum bending stress of approximately 1300 N/mm^2 for the standard specimen design used. The maximum bending stress was calculated from the formula:-

$$M = \frac{fbt^2}{6}$$

where M = bending moment
f = bending stress
b = strip width
t = strip thickness

With such fatigue machines, the applied bending moment is measured using a dynamometer spring which is connected to two gauges by a measuring arm. Calibration charts, which relate dial gauge deflection to bending moment for each dynamometer spring, are provided with each machine. Before fatigue testing, the calibration curve for each machine was checked using a system of standard weights and free-running pulleys. This calibration check was carried out in the direction of bending to be used in the fatigue tests.

In all cases, fatigue testing was carried out from an initial bending stress of zero to a series of maximum bending stresses. The mode of testing was such that the peened face of every specimen was stressed in tension. Fatigue data for the shot peened flat strip specimens are presented in Fig. 2. In the case of the strain peened specimens no failures occurred up to the maximum testing stress of 1300 N/mm^2.

3.3.2 Modified Specimens

Using the standard specimen, as shown in Fig. 1, it was not possible to obtain any limited life data after strain peening, even at the maximum bending stress attainable (i.e. 1300 N/mm^2). In order to increase the maximum bending stress available, a small number of modified specimens were produced. Their design was similar to that of the standard specimen with the exception that the specimen waist was reduced to 13.5 mm. The radius of curvature was maintained at 38.1 mm to prevent any stress concentration effects. Using this modified specimen, the maximum bending stress attainable was raised to around 1900 N/mm^2. Following recalibration of the fatigue machines, a total of eight specimens of the modified type were strain peened under the same conditions as the standard specimens and were subsequently fatigue tested. The results are shown in Fig. 3.

For comparison purposes, the fatigue data for conventionally shot peened specimens taken from Fig. 2 are reproduced in Fig. 3.

4. DISCUSSION

The results obtained demonstrate clearly the beneficial effects of strain peening on the bending fatigue properties of CS 80 strip. The conventionally shot peened specimens showed a fatigue limit of 600 N/mm^2, compared to a fatigue limit of 1340 N/mm^2 for strain peened specimens. The few limited life results obtained also suggest increases in fatigue strength of about 100%. This improvement is greater than that achieved in a similar investigation described in the literature(3). In the latter case, however, the specimens had been made from hardened and tempered low alloy spring steel strip with a thickness of 4.9 mm. Peening had been carried out using chilled cast iron shot, which is known to be less effective in increasing fatigue performance than cast steel shot.(4) Moreover, the use of thicker specimens may have tended to reduce the benefits of strain peening.(5)

A satisfactory general explanation of the effects of strain peening on the fatigue performance of springs has yet to be advanced. It has been claimed that the increase which can be obtained in bending fatigue life is due solely to an increase in the magnitude of the residual stress at the specimen surface.(1) This theory has been supported experimentally(3) but there remains some disagreement regarding the stress level for strain peening which is required to produce the optimum fatigue performance. In one case, strain peening at 50% of the tensile elastic limit is recommended, while in the other 80% is quoted. However, since fatigue failures in shot peened specimens are frequently of sub-surface origin, any explanation of the effects of strain peening must necessarily consider the residual stress distribution below the specimen surface.

Sub-surface fatigue cracks in shot peened specimens are initiated at a point adjacent to that at which the nature of the residual stress changes from compressive to tensile. This is sometimes called the "crossing point". Adjacent to this point, the effective stress has its maximum value, being the algebraic sum of the applied stress at that depth and the residual tensile stress. When a flat strip specimen is bent in uniaxial tension, the magnitude of the applied tensile stress decreases with distance below the convex surface. Hence, for a given applied bending stress, increasing the depth of the crossing point decreases the effective stress at the sub-surface crack initiation point. That is to say that, if the depth of the crossing point can be increased, the fatigue life at a given bending stress will be increased. It has been suggested that this is precisely the effect produced by strain peening(2); in this case, the authors concluded that the important parameter is the depth of peening, rather than the magnitude of the residual stress induced at the surface. A similar explanation has also been suggested when comparing the effects of conventional and high hardness shot peening on the fatigue properties of torsion bars.(6)

However, the magnitude of the residual stress at the surface must be of importance since, if this is too low, the maximum effective stress may occur at the surface rather than below it. This would be likely to occur at high bending stress, resulting in a reduced fatigue life. On the basis of theoretical considerations, it may be concluded that, in this case, increases in both the magnitude and the depth of the residual compressive stress induced by strain peening contributed to the improved fatigue performance. For a given specimen size and hardness, these two parameters are dependent upon: the hardness and momentum of the peening medium; the duration of peening; and the applied stress under which strain peening is carried out. Further investigations on strain peening should therefore be concerned with the effect of these variables on the fatigue performance resulting from strain peening, in order to determine the optimum operating conditions. The present investigation has indicated the kind of improvement in the fatigue performance of CS 80 strip that can be achieved by strain peening; in future, testing equipment capable of much larger bending moments should be used in order to produce results of a more quantitative nature.

5. CONCLUSIONS

1. The bending fatigue properties shown by hardened and tempered CS 80 strip after strain peening are substantially better than those produced by shot peening alone. This increase is approximately 100% in terms of allowable stress for a given fatigue life.

2. In assessing the influence of experimental variables on the effectiveness of the strain peening operation as applied to flat springs, both the magnitude and depth of the induced residual stresses must be considered.

6. REFERENCES

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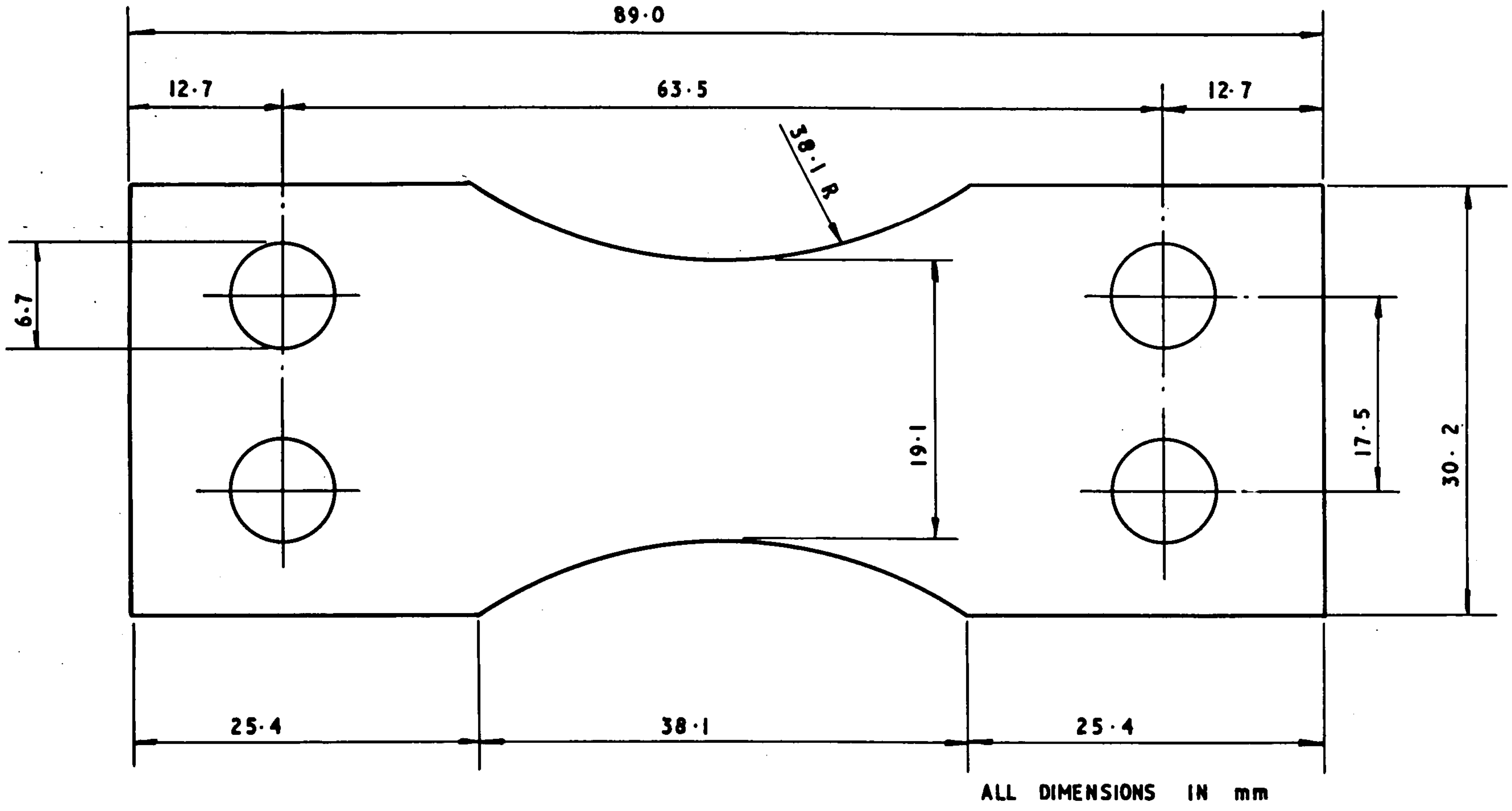
TABLE I CHEMICAL COMPOSITION OF CS 80 STRIP

	%C	%Si	%Mn	%S	%P
Nominal	0.75 -0.85	0.05 -0.35	0.50 -0.90	0.050 Max	0.050 Max
Actual	0.80	0.24	0.69	0.029	0.016

TABLE II TENSILE PROPERTIES OF CS 80 STRIP

Tensile Strength		L of P		0.1% PS		0.2% PS		Elong.	R of A	Hardness
tonf/in^2	N/mm^2	tonf/in^2	N/mm^2	tonf/in^2	N/mm^2	tonf/in^2	N/mm^2	%	%	HV 20
105.1	1620	84.9	1310	89.7	1385	91.1	1405	6.0	7.1	500-510



ALL DIMENSIONS IN mm

FIG. I. STANDARD FATIGUE TEST SPECIMEN.

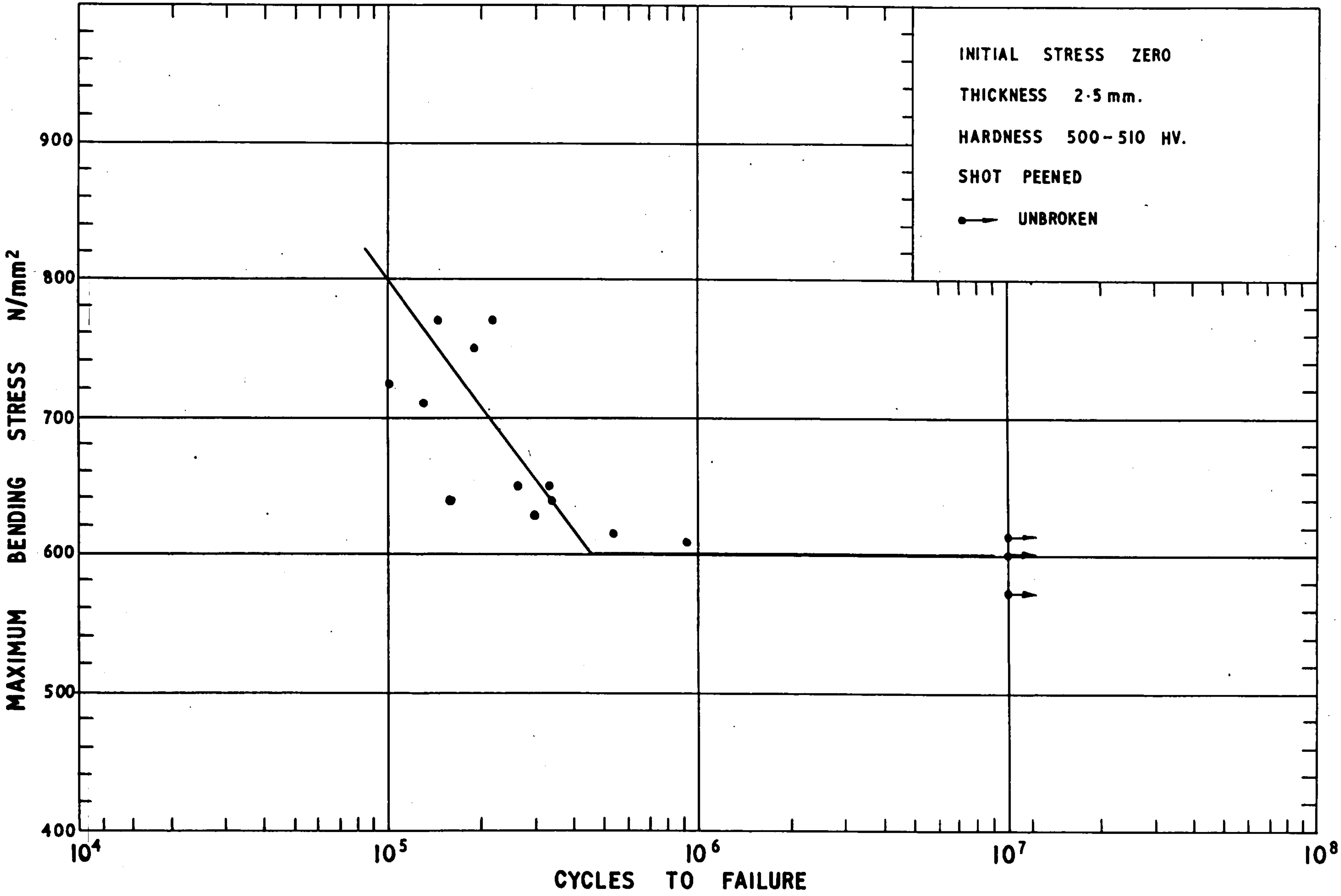


FIG. 2 S/N CURVE FOR SHOT PEENED CS 80 STRIP.

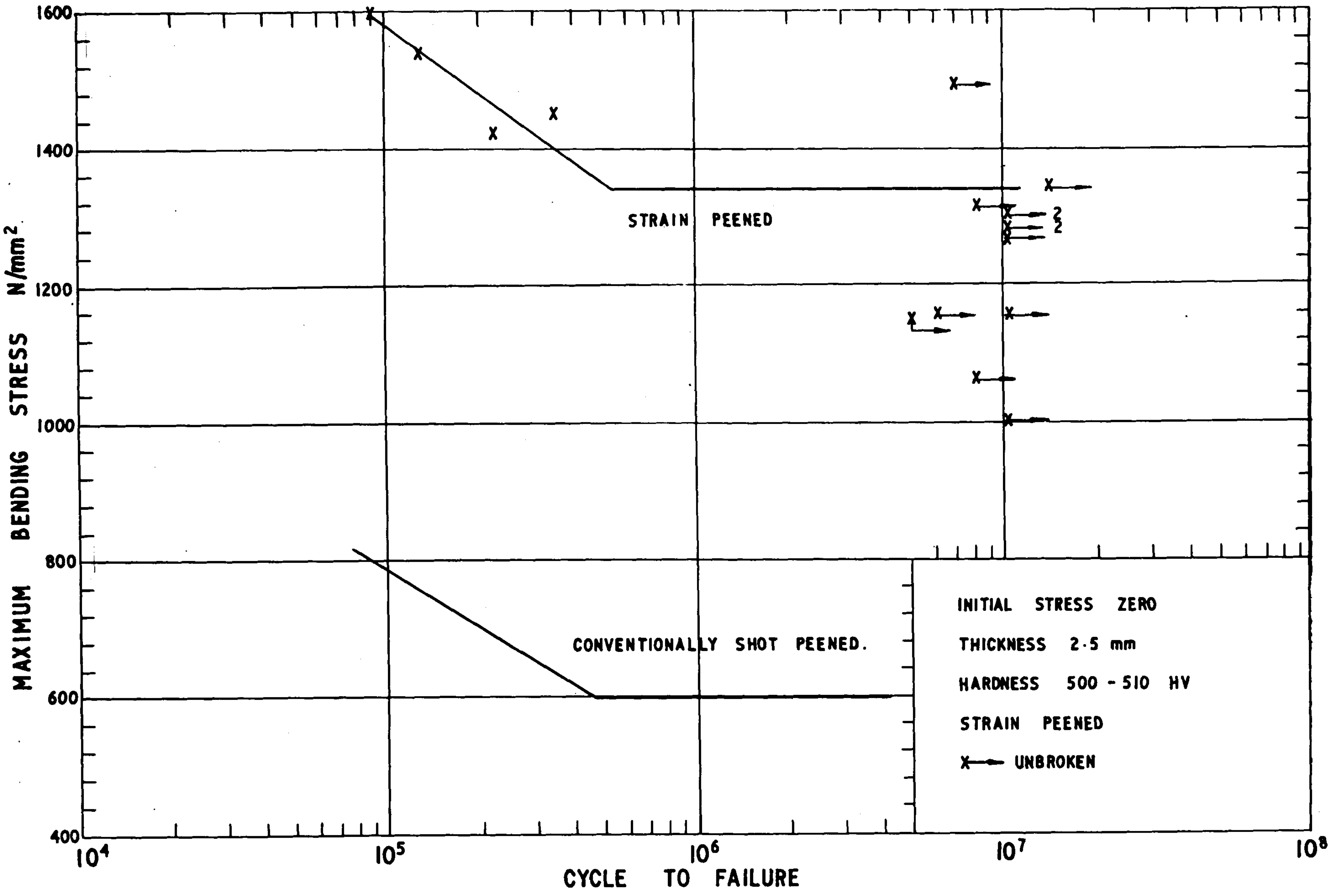


FIG. 3 S/N CURVE FOR STRAIN PEENED CS 80 STRIP.