THE SPRING RESEARCH AND MANUFACTURERS' ASSOCIATION

SHOT PEENING AND THE EFFECT OF SHOT SIZE ON SPRING PERFORMANCE

by

G.C. Bird, B.Sc.

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SUMMARY

The purpose of this investigation was to examine the effect of shot peening on the properties of helical compression springs of various materials and wire sizes, using cast steel shot sizes between S70 and S550. The springs, made from wire to BS 1408, BS 2803 and BS 2056 (En 58A) materials, were shot peened in the Association's Wheelabrator 'Tumblast' machine. With each shot size used, the intensity of peening was determined by the use of an Almen strip, several tests also being carried out on the strips to measure the surface roughness and assess the compressive stress produced by the peening. After the springs had been shot peened, they were stress relieved and prestressed before carrying out stress relaxation and fatigue tests.

It was found that the larger the size of shot used, the greater were the Almen arc rise and the residual compressive stress, and the poorer the surface finish.

In the stress relaxation tests, the shot peened springs relaxed more than the unpeened ones - the larger the size of shot used, the greater the relaxation. In the fatigue tests, shot peening was shown to improve the endurance limit of all the springs, the improvement being most marked with the smaller shot sizes. In general, the largest increase was obtained when the shot size was less than a quarter of the wire diameter.

In addition to the work described above, tests were also carried out to assess the effect of shot velocity by increasing and decreasing the speed of the impellor. It was found that raising the energy

of the shot, by raising the speed and keeping the shot size constant, increases the Almen arc rise obtained and the residual stresses induced, but also increases the surface roughness. Of the springs peened with S330 shot at different velocities, those peened at the slowest speed had the best fatigue performance.

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1. INTRODUCTION

Shot peening is now a well established method of improving the fatigue performance of helical compression springs and the effects on different materials have been described in several research reports. The process consists of bombarding the springs with small pieces of shot, usually cast steel or conditioned cut wire, whereby compressive stresses are induced in the surface and immediate sub-surface layers of the wire, which act in opposition to the tensile stresses caused by the loading of the spring. The Association has carried out several investigations into the increase in safe working stress than can be achieved by peening but only in one report(1) has the effect of shot size on the fatigue performance of springs been considered. For that study, three sizes of shot and one spring material were used. In this present investigation the phenomenon has been examined in more detail using a wider size range of shot on a selection of spring materials. In addition, the various parameters involved in the peening operation have been examined, together with measurement of the effect of shot size on several spring parameters.

2. SPRING DESIGNS AND MATERIALS

The springs used were made from three different materials: cold drawn patented carbon steel wire to BS 1408M Range 2; oil hardened and tempered carbon steel wire to BS 2803 Grade II; and cold drawn austenitic stainless steel wire, En 58A to BS 2056. The materials were tested in various wire sizes between 1.22 and 5.95 mm diameter, springs of each design being shot peened with six sizes of shot, except in the case of the smallest wire diameter, when the largest shot size was not used. The ratio of shot size to wire diameter varied, therefore, from 0.03 to 0.9. This range was larger than that of the previous work and, in addition, the solid stress was increased to approximately 70% of the 'as received' tensile strength of the wire, in order to eliminate difficulties encountered previously in fatigue testing to failure some of the springs.

Details of the spring designs used are shown in Table I.

3. SHOT PEENING MEDIUM

The medium used for peening the springs was "Wheelabrator" cast steel shot, sizes S70, S110, S230, S330, S460 and S550, the number indicating the nominal size of the shot in in. x 10^{-4}. Before being used, samples of each grade were examined, hardness measurements taken and the shot was sieve tested. The hardness measurements are given in Table II and the graphs showing the distribution of size in each grade of shot in Figs. 1 and 2.

4. SHOT PEENING PLANT

The equipment used to shot peen the springs was a Wheelabrator "Tumblast" machine, model WTBOA, which is illustrated in Fig. 3. The springs to be peened are tumbled on a continuous rubber belt; shot from an overhead storage hopper is fed to the centre of a bladed wheel and thrown on to the springs in the cabinet by centrifugal force. A small impellor rotates within the main impellor and carries the shot to an opening in a stationary control cage where it is discharged into the bladed section of the wheel. At this point, the shot is picked up by the inner end of the blades and accelerated in its passage to periphery of the wheel. The position of the blast stream in relation to the wheel can be altered by rotating the control cage and, for every size of shot used, it needed to be reset to obtain the shot pattern in the centre of the cabinet.

Once the shot has passed the springs and the holes in the rubber belt, it falls into a trough. From this it is lifted in a bucket elevator and as it is being raised the finer particles are removed by an extractor fan. Once the shot is at the top of the elevator it passes through an air wash separator, where broken and small shot is again removed, into the storage hopper.

The amount of shot thrown on to the springs is controlled by a butterfly valve which has four settings. This controls the rate at which coverage is otained, full coverage taking longer on setting 1 than on setting 4 (full open) although the maximum arc rise is not affected. With the usual setting of No. 3, the flow of S330 shot through the wheel is about 350 lb/min.

The intensity of peening for any given shot size depends upon its velocity, this being governed by the wheel size and speed. The wheel size of the machine was 12 inches and for the majority of the tests the wheel speed was 37.5 Hz, giving a shot velocity of about 36 m/sec. In order to examine the effect of the shot velocity, two trials were carried out with wheel speeds of 25 Hz and 48.3 Hz. Because of the limitation of motor size, only the smallest opening could be used at the highest speed; otherwise the wheel speed dropped considerably.

5. MEASUREMENT OF PEENING INTENSITY

The usual measurement of peening intensity is the Almen arc rise, determined using the Almen strip, holder and gauge(2). The method is based upon the principle that, if a thin strip of metal is clamped and shot peened on one surface only, the compressive stresses in this side cause the strip to take up a curved shape when it is released, the amount of curvature being related to the effective intensity of the peening. The strips used in the work were Almen A strips, the specification for which is shown in Fig. 4. The gauge, commonly referred to as the Almen No. 2 gauge, for determining the curvature of the test strip is shown in Fig. 5. The curvature of the strip is determined by a measurement of the height of the combined longitudinal and transverse arc across standard chords. As can be seen from Fig. 5, the arc height is obtained by measuring the height of a central point on the non-peened surface from the plane of four balls forming the corners of a specified rectangle. The standard designation of peening intensity includes the gauge reading of arc height and the test strip used. For example, 0.013 A2 signifies that the arc height of the peened Almen A test strip as measured on the Almen No. 2 gauge was 0.013 in.

6. CALIBRATION CURVES

For each shot size used, a calibration curve was produced before peening the springs. A number of Almen strips were placed in the machine, together with a batch of springs to act as ballast, which were peened in the usual manner. At set intervals, two strips were removed and their arc rise measured. By this method a curve of Almen arc rise against exposure time could be plotted which enabled the maximum arc rise and time taken to reach full coverage to be determined for each size of shot.

The calibration curves for the six shot sizes at the normal wheel speed of 37.5 Hz are shown in Fig. 6 and for the S330 shot at different wheel speeds in Fig. 7.

7. MEASUREMENTS ON ALMEN STRIPS

In order to estimate the effect of the different sizes of shot on the springs, various tests were carried out on Almen strips peened at the same time as the springs. These tests involved the measurement of the Almen arc rise, to give an indication of the compressive stress in the strip, and a Talysurf reading to give a measurement of the surface finish. The results of the two tests are given in Table III.

In addition, twelve Almen strips were sent to Lanchester Polytechnic, where the surface residual stress for both the longitudinal and transverse directions of the peened face were measured. These macro-stress measurements were carried out using a standard two-exposure X-ray diffractometer, the measurements being taken at the centre of the specimen. Details of the method used are given in the Appendix and the residual stress results are given in Table IX.

In order to estimate the residual stress in the strip while still under restraint, the radii of curvature for the major axis, R_x, and minor axis, R_y, of each specimen were obtained using a simple direct-comparison method. The radii of curvature were substituted into the classical thin plate bending formulae$^{(3)}$:

$$(1) \qquad \sigma_x = \frac{Et}{1-\nu^2}\left[\frac{1}{R_x} + \frac{\nu}{R_y}\right]$$

$$(2) \qquad \sigma_y = \frac{Et}{1-\nu^2}\left[\frac{1}{R_y} + \frac{\nu}{R_x}\right]$$

where σ_x and σ_y = stresses at distance, t, from the neutral plane

E = elastic modulus (207 kN/mm^2)

ν = Poisson's ratio (0.3)

The surface stress values were obtained by substituting $t = \frac{1}{2}$ x strip thickness. The calculated values of σ_x and σ_y given in Table X are an indication of the stresses induced in the springs by the shot peening process.

8. SHOT PEENING PROCEDURE

For each size of shot, the machine was cleaned out thoroughly, the new shot introduced, the control cage adjusted to give the shot pattern in the centre of the cabinet and the calibration curve produced as described in Section 6.

The free length of springs of each design to be shot peened was measured and the batches identified. The springs were then peened for a period of time long enough to give complete coverage, generally 30 minutes; they were removed and the free length re-measured, and then given a low temperature stress relieving treatment of 225°C for half-an-hour. Finally, the springs were fully prestressed before any tests were carried out, the free length being measured before and after prestressing.

For each spring design, a batch of springs was used as a control group, not being shot peened but being subjected to all the tests.

9. STRESS RELAXATION TESTS

In order to assess the effect of the size of shot on the relaxation of springs at elevated temperatures, springs from three different materials which had been peened with all six sizes of shot were subjected to stress relaxation tests together with batches of similar unpeened springs.

The springs were load tested, clamped on Monel bolts at various stress levels and held in an air circulating furnace for either 72 or 168 hours. After being removed from the furnace, they were load tested again to determine the loss in load, and hence relaxation, that had occurred. Details of the tests carried out are given in the table below and the results obtained are shown in Figs. 8, 9 and 10.

Material	Wire Diameter (mm)	Stress Levels (N/mm^2)	Temp. (°C)	Time (h)
BS 1408M Range 2	3.15	500,700,900	125	72
BS 2803 Grade II	4.0	300,500,700,900	150	72
BS 2056, En 58A	1.22	400,600,800,1000	300	168

10. FATIGUE TESTS

Springs of six different designs which had been peened with the various sizes of shot were fatigue tested on the Association's forced motion fatigue testing machine to produce a series of S/N curves, all with an initial stress of 100 N/mm^2. In order to assess the improvement in fatigue properties a batch of unpeened springs of each design was first tested to produce a base curve.

The S/N curves produced for each spring design are shown in Figs. 11-16. The sloping portion of each curve is the best fit line produced by "least squares" analysis of the broken spring data and the fatigue limit determined from the springs which survived 10 million cycles without failure.

11. DISCUSSION OF RESULTS

11.1 Shot

There is no British Standard specification for shot for use in peening, except for a BSCRA specification for steel shot for use in foundry applications. There are, however, S.A.E. specifications for cast steel shot, J444, J827, which cover permitted size range and hardness of shot respectively. A summary of the shot size requirements is given in Table IV. All the shot passed the size specification except the S70 and S110 shot, which included shot greater than the maximum permissible size. The average hardness of the cast steel shot particles should lie within the limits 390-510 HV (40-50 Rc), a large range being necessary to allow for differences in hardness which are inherent in the manufacturing process. All the sizes conformed to this specification with the possible exception of the S70 shot whose hardness was difficult to measure because of the small size and the low test load applied. The effect of shot hardness has been examined previously(4) over a wider range, 255-850 HV; shot hardness was found to have no influence on the ultimate endurance limit of the spring.

11.2 Calibration Curves

The calibration curves for the shot peening plant shown in Fig. 6 indicate that the larger the shot, the greater the arc rise produced. After peening for a period of one hour a linear relationship is obtained between the measured arc rise and the shot size. The calibration curves for the S330 shot using three different wheel speeds (Fig. 7) show that, as the energy of the shot is increased by the extra velocity, the greater is the arc rise obtained in the Almen strip. Again, the power of the machine limited the volume of shot that could be thrown at the highest speed, lengthening the time taken to achieve full coverage.

11.3 Surface Finish Measurements

The effect of the peening operation on the surface condition can be seen in Table III where it is apparant that peening increases the roughness of the Almen strips, the CLA value increasing with the size of shot used to a maximum of 3.8 μm with the S550 shot compared with the original value of 0.7 μm. As a comparison, typical results of CLA measurements on unpeened spring wires have given values of 0.15-0.25 μm for hard drawn carbon steel wire, 0.4-0.45 μm for oil tempered wire and 0.25-

0.9 μm for stainless steel wire.

11.4 Free Length Variation

Tables V to VIII show the average free length of four of the spring designs used after shot peening, after the L.T.H.T following peening and after prestressing, together with the free length after prestressing of the unpeened springs. As can be seen in the tables, the size of shot does not have any noticeable effect on the free length value after peening, stress relieving or prestressing. This confirms other recent work carried out by the Association(5) which showed that, for springs manufactured from material to BS 5216 and given a stress relieving heat treatment between 200°C and 250°C after shot peening, the solid stress after prestressing was the same as that of similar unpeened springs. In the previous investigation into shot size(1), however, the results showed that springs peened, stress relieved at a similar temperature and then prestressed were always shorter than the unpeened springs, the free length decreasing with shot size. The difference between that and the other two investigations was that the springs were given a L.T.H.T. after coiling at 250°C, very close to the stress relieving temperature of 225°C after peening. In the work described in this report and that for the BS 5216 material, however, the L.T.H.T. after coiling was at 350°C for carbon steel springs and 450°C for the stainless steel springs.

11.5 Stress Relaxation Results

Recent work carried out by the Association on the stress relaxation properties of springs from high tensile carbon steel wires(3,4) has shown that when unpeened and shot peened springs have been held at the same stress and temperature, the shot peened springs exhibit greater relaxation. The data so far produced have only related to springs peened with one size of shot. The stress relaxation tests on springs peened with different sizes of shot cover three different materials and temperatures. The results are shown in Figs. 8-10, in which the effect of peening the springs with larger shot on the stress relaxation at a particular stress level can clearly be seen. In all cases the shot peened springs relaxed more than similar, unpeened ones; the larger the shot, and hence the greater the amount of residual stress induced by the peening, the greater was the relaxation. It was also noticeable that, for similar springs, the increase in relaxation with increasing shot size was more marked at the higher stress levels.

11.6 Fatgiue Properties

11.6.1 Review of previous work

Very little information has been published on this aspect of shot peening, two papers by Zimmerli(4),(6) and one previous report by the SRAMA(1). The two papers by Zimmerli describe work using shot of 0.016 and 0.048 in nominal size on springs manufactured from carbon steel wire of 4.11 mm (0.162 in) and 3.75 mm (0.148 in) diameter. In the first investigation(4), fatigue tests using either size of shot gave the same fatigue limit; the limited life data however, were superior with the smaller size of shot.

In the paper(6) presented to the SAE Iron and Steel Technical Committee, three sizes of shot between 0.016 in and 0.046 in were used to shot peen springs made from one batch of 3.75 mm (0.148 in) diameter, oil tempered valve spring wire. The conclusions drawn are summarised below:

1. Throughout the range of hardness in the shot used (275-820 HV) there was no significant effect on the ultimate endurance limit of the springs.

2. The size of shot did not affect the endurance limit when 0.016 or 0.028 in shot was used. When 0.046 in shot was used, the endurance limit of the springs was not as great but was still greater than for the unpeened springs.

3. There was no relationship between arc height and endurance limit.

In the conclusions of the above paper it was pointed out that some company drawings often carry merely an arc rise as the peening specification. Actually, such a specification could lower the quality of peening since, by adding a little oversize shot to the machine, it is possible to raise the arc height quickly, but not the spring endurance level which may be less than anticipated.

The most recent investigation into the effect of shot size on spring fatigue performance was carried out by the SRAMA using patented cold drawn wire in three sizes - 1.2 mm, 2.36 mm and 3.6 mm, and three shot sizes - S110, S330 and S550. The results showed that where the shot was larger than a quarter of the wire diameter, the fatigue limit was below the optimum and decreased with increasing shot size to the point at which the shot and wire were of the same diameter, when the ultimate endurance of the shot peened springs was less than before peening.

Although, as mentioned earlier, only one previous investigation has been carried out to examine the effect of shot size on the fatigue performance of helical compression springs, work has been carried out on spring materials when stressed in bending.

In one case(7), specimens manufactured from En 42 material were machined, hardened and tempered to 530 HV and tested in the rotating bending mode. The specimens, 3.6 mm in diameter, were peened with three sizes of shot of nominal diameters 0.036 0.036 in, 0.059in and 0.089 in. The depth of the surface craters was estimated at 0.001 in for the smallest shot and 0.006 in for the largest. At high stresses, it was found, the fatigue performance of the specimens peened with 0.059 in shot was best. However, the specimens peened with the smallest size of shot had the highest fatigue limit.

In another investigation(8), leaf spring type specimens were made from En 48 material, ground to 4.9 mm thick, and hardened and tempered to 500 HV. The specimens were shot peened using three sizes of shot - S130, S230 and S660 - by air blasting to give Almen arc rises of 0.010, 0.17 and 0.035 respectively. Fatigue testing was carried out in unidirectional bending through a stress range of 0 - 1380 N/mm^2 and the average fatigue life of specimens that had been peened to full coverage was

100×10^3 cycles for the S130 shot, 65×10^3 cycles for the S230 shot and 50×10^3 cycles for the S660 shot. From this and other results, it was concluded that, although 'coverage' is an important variable, coverage beyond a certain value does not produce further fatigue improvement. Furthermore, exposure times corresponding to the point at which the Almen C strip height curve begins to flatten was adequate for material of the type tested.

11.6.2 Analysis of present results

The effect of shot size on the fatigue properties of the springs, as shown in Figs. 11 to 16, is probably the most interesting feature of this work.

The lines on the S/N curves represent the best-fit lines as determined by the 'least squares' analysis of the broken spring data. On each S/N curve are shown the best-fit lines for each of the different shot size used and also for the springs in the unpeened condition. In certain cases, because of the limited testing range, the correlation coefficient of the line was less than 0.9; this is indicated by a dotted line on the sloping portion of the curve.

The results of the fatigue tests on the cold drawn carbon steel wire to BS 1408M Range 2 are shown in Figs. 11 and 12. It can be seen that for both wire sizes the effect of increasing the shot size is not only to reduce the fatigue limit but also the fatigue strength at working stresses above the fatigue limit. In addition, the effect of the largest shot sizes used, S460 and S550, was to reduce the fatigue performance at certain stress levels below that of the unpeened springs.

The springs made from oil tempered 5.74 mm diameter wire to BS 2803 also showed a similar maximum increase in the fatigue limit. As can be seen on the S/N curve (Fig. 13) the fatigue limits produced by the four smallest sizes of shot were very similar, within 50 N/mm^2 of one another, and because of the proximity of the fatigue limit to the maximum testing stress, the sloping portions of the S/N curves could not be assessed accurately. The maximum increase in the fatigue limit was 32%, similar to that of the other two carbon steel wires, although the wire diameter was larger, and the optimum shot size ratio was again about 0.1.

Springs made from two sizes of stainless steel wire, En 58A to BS 2056, were tested. The results for the 1.22 mm diameter wire as shown in Fig. 14 and those for the 5.89 mm diameter wire in Fig. 15. In the case of the smaller wire, there was a very noticeable increase in fatigue performance as the shot size was reduced, the S/N curves for S70 and S110 shot being very similar. Because of the lower fatigue performance of the unpeened springs there was a much larger increase in the fatigue limit than with the carbon steels, a maximum of 55% with the S70 and S110 shot. Furthermore, because of the low fatigue limit of the 5.89 mm diameter stainless steel material in the unpeened condition, the largest shot gave an improvement of 80%. Again, the fatigue limit was so close to the solid stress of the spring that very little difference could be detected between the fatigue limit produced by the four smallest shot sizes, all of which doubled the fatigue limit from 370 N/mm^2 to about 740 N/mm^2.

To summarise the fatigue data, the percentage increase in the fatigue limit was calculated for each shot size/wire diameter ratio. The curves for the six carbon steel materials tested in this and the previous work are plotted in Fig. 16. The data for the 3.15 mm and 1.63 mm diameter wires to BS 1408M Range 2 and the 5.74 mm diameter wire to BS 2803 give similar curves to that previously obtained for springs from BS 1408C Range 2. Except where the fatigue limit was affected by the solid stress of the springs, the maximum increase for all these materials was between 30% and 35%.

From the summary of the fatigue data in Fig. 16 it is apparent that the greatest increase in fatigue performance is obtained when the shot size used is less than about 10% of the wire diameter for carbon steel springs.

It can also be seen that for the smaller wire diameters the same lift in fatigue properties can be obtained with a larger shot size/wire diameter ratio. Thus with a wire diameter of 1-1.5 mm a shot size ratio of 0.5 will still give an increase of above 20% whereas the same shot size ratio on 3 or 4 mm diameter wire would give very little increase in fatigue performance. This is very important in practice because it means that a single shot size can be used which will give a good increase in fatigue properties over a wide range of wire sizes.

For the two stainless steel wires; 1.22 mm and 5.89 mm diameter material to En 58A, a similar summary of the fatigue data is given below:

Shot Size	Wire diameter 1.22 mm		Wire diameter 5.89 mm	
	Shot size / Wire dia.	% Lift in Fatigue Limit	Shot size / Wire dia.	% Lift in Fatigue Limit
S70	0.15	53	0.030	95
S110	0.23	55	-	-
S230	0.48	37	0.099	105
S330	0.69	25	0.14	105
S460	0.96	5	0.20	105
S550	-	-	0.24	82

Again it can be seen that shot size/wire diameter ratios between 0.1 and 0.25 gave the greatest improvement in fatigue properties for both wire sizes, though there was a slight reduction where the ratio was very much less than 0.1. Even with very fine shot, a large increase in the fatigue properties was noticed, although the Almen arc rise induced by the shot peening was less than with the larger shot. The surface roughness of the springs of peened with the S70 and S110 shot was much less than after peening with S550 shot, which may account for the fact that the S550 shot always gave the poorest fatigue performance.

It should be borne in mind, however, that all the wires used had little or no decarburisation. On springs which have been hardened and tempered after coiling, therefore, larger shot may be necessary to penetrate any surface decarburisation present and induce residual stresses in the body of the material.

11.7 Surface Stress Measurements

The measured surface residual stress values given in Table IX show two general features. Firstly, all of the strips have a surface compressive residual stress (as indicated by the minus sign), which is to be expected from the shot peening process. Secondly, the strips with the greatest Almen arc rise have the lowest levels of surface compressive stress. This is in conflict with the fact that the greatest curvature corresponds to the most intense peening. This apparent anomaly can be explained by the fact that, when the strips are released from the Almen block, bending takes place which gives a corresponding relief of surface compressive stress which is proportional to the induced curvatures of the specimen. The values given in Table X are an indication of the amount of relief which could be expected. These values have also been combined with those from Table IX to give the stresses in the 'as clamped' position, which relate to the surface stress induced in the spring. It can be seen that the use of a larger shot with a greater arc rise induces larger residual surface compressive stresses. The summation of the calculated residual surface stresses in the 'as clamped' position is also shown graphically in Fig. 17, in which the residual stress is plotted against both the size of shot and the Almen arc rise produced. It can be seen from this graph that the residual stress increases as a function of both these parameters. The fact that the fatigue performance does not improve as the residual surface stress increases may be attributed to the roughening of the surface produced with the larger shot sizes, which more than offsets the increase in the residual stress value.

11.8 Effect of Wheel Speed

In order to assess the effect of varying the shot velocity on the fatigue performance of springs, the impellor speed was changed by altering the pulley ratio from the motor. Thus, in addition to the normal wheel speed of 37.5 Hz, faster and slower speeds were obtained - 48.3 Hz and 25 Hz. At the highest speed, the volume of shot that could be thrown was restricted by the size of the wheel motor but this did not affect the maximum arc rise that was obtained.

Calibration curves for the shot peening plant were produced for one shot size, S330, and for each of the three speeds. These are shown in Fig. 7. Almen strips peened at the three speeds were subjected to the same tests as described previously and the results for Almen arc rise, surface finish and residual stress measurement are given in Table XI. As can be seen, the Almen arc rise and the residual surface stress increase as the energy of the shot is increased by raising the wheel velocity. Furthermore, as the speed is increased, the depth of the shot indentations, which is reflected in the average CLA value, increase.

Two batches of springs only, made from 1.63 mm and 3.15 mm diameter wire to BS 1408M Range 2, were shot peened for 30 minutes at both additional wheel speeds. The springs were then stress releived and prestressed before being fatigue tested, under the same conditions as the other springs, in order to assess the effect of shot velocity on the fatigue performance. The two S/N curves produced are shown in Figs. 18 and 19, in which the best fit lines are shown for the fast and slow speeds. It will be noticed that, allowing for the experimental scatter in the results, springs shot peened at the slow speed had a longer fatigue life than those peened at the two faster speeds. This is particularly noticeable in Fig. 18 for the springs from 1.63 mm diameter wire where the three best-fit lines radiate from a point near the maximum testing stress and the slope of the S/N curves decreases as the Almen arc rise decreases - a similar pattern to that obtained by directly altering the shot size.

The results of the fatigue tests indicate that increasing the shot velocity in order to increase the Almen arc rise only serves to reduce the fatigue strength of the springs. By reducing the wheel speed a smaller motor can be used to throw the same weight of shot and an improvement in fatigue performance can be obtained. No stress relaxation tests were carried out but it is probable that the results would be similar to those obtained before, when the greatest relaxation was obtained with the springs peened to the highest Almen arc rise.

12. CONCLUSIONS

1. The larger the shot used in peening, the larger the Almen arc rise obtained and the greater the residual compressive stress induced, but also the rougher the surface finish.

2. With suitable low temperature heat treatment after shot peening, the solid stress after prestressing is the same for both peened and unpeened springs.

3. At elevated temperatures, shot peened springs relax more than unpeened springs and the larger the shot size used, the greater the amount of relaxation.

4. All springs peened with S550 shot, which gave the largest Almen arc rise, exhibited the poorest fatigue performance of the shot peened springs.

5. The largest improvement in fatigue performance was obtained when the shot size was between a quarter and one tenth of the wire diameter for stainless steel wire springs and about one tenth of the wire diameter for carbon steel wire springs.

6. The maximum improvement in fatigue limit that could be obtained with carbon steel springs was approximately 30% but was much greater for stainless steel, being between 50% and 100% depending upon the wire sizes.

7. Increasing the velocity of the shot increases the Almen arc rise obtained and the residual stresses induced but also increases the surface roughness.

8. Of the springs with S330 shot at different velocities those peened at the slowest speed had the best fatigue peformance.

13. PRACTICAL APPLICATIONS

When considering the practical case of a spring manufacturer using a shot peening plant where a range of materials and wire sizes need to be handled, it is obvious that the shot in the plant cannot be changed to give the optimum performance for every batch of springs. It is necessary, therefore, to compromise and depending upon the number of machines available to choose a shot size or sizes that will be suitable for all the springs to be peened in the particular machine. The information given in this report can be used as a guide to shot selection and other points which need to be taken into consideration are as follows:

1) The spring design may limit the improvement in fatigue properties that can be achieved. This was indicated in the previous work where the maximum increase in the fatigue limit was governed by the solid stress* of the spring as well as the size of shot.

2) The results of this work indicate that, for carbon steel wire, although the maximum increase in fatigue performance is obtained with a shot size about 10% of the wire diameter, for wire sizes about 1-1.5 mm diameter a marked improvement is still obtained when the shot is half the size of the wire. Thus, if only one plant is available, a single shot size can be chosen which will still give an effective increase in fatigue performance over a wide range of wire sizes.

3) In order to obtain a beneficial effect from shot peening the shot needs to strike the inside surface of the wire so the use of a smaller shot is necessary where springs have a low index or little space between the coils.

4) When designing springs for fatigue applications, it should be borne in mind that the improvement in fatigue life produced by shot peening decreases as the initial stress on the spring is increased. The fatigue tests in this report have all been carried out at an initial stress of 100 N/mm^2 so the percentage improvements in fatigue limit

of springs working with an initial stress greater than this will be smaller than those quoted.

5) The data produced in this report using the Association's plant gives an indication of the improvement that can be achieved. It is important to realise that this can only be achieved and maintained if the plant is properly supervised. The major variables affecting the process are the shot, the average size of which will gradually reduce, and the position of the blast stream which should be checked regularly to see that the springs are being peened rather than the walls of the cabinet. The easiest method of checking these parameters is by use of Almen strips placed at various positions in the cabinets. The arc rise can than be checked to see that an even shot pattern is being maintained and the correct intensity is being achieved.

6) Where there is more than one peening plant in operation, the shot in each should be chosen such that when the largest shot has broken down to an inefficient size it can be used in the next smallest machine.

14. REFERENCES

1. BIRD G.C. "An Investigation into the Effect of Shot Size in Shot Peening". SRA Report No. 217.

2. "Test Strip, Holder and Gage for Shot Peening". S.A.E. Standard J442.

3. TIMOSHENKO S. "Strength of Materials, Part II". Van Nostrand, 1956, p. 87.

4. ZIMMERLI F.P. "Shot Blasting and Its Effect on Fatigue Life". A.S.M. Surface Treatment of Metals Symposium, 1941.

5. BIRD G.C. "The Low Temperature Heat Treatment of Springs Manufactured from Patented Cold Drawn Carbon Steel Wire". SRA Report No. 266.

6. ZIMMERLI F.P. "Effect of Shot Type on Spring Fatigue Life". SAE Journal, Nov. 1948.

7. COOMBS A.G., SHERRATT F. and POPE J.A. "An Analysis of the Effects of Shot Peening upon the Fatigue Strength of Hardened and Tempered Spring Steel". International Conference on Fatigue of Metals, London, 1956.

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APPENDIX

The Two-exposure X-ray Diffractometer Method of Residual Stress Analysis

Introduction

This method is well established as a means of accurately determining residual macro-stresses. It is based upon the conversion of crystal lattice strains measured at angles to the sample surface, corresponding to residual macro-stresses parallel to the sample surface.

A high-angle diffraction line is used to determine the elastic strain perpendicular to the surface, ε_z , and that at an angle to the surface, $\varepsilon_{\phi\psi}$, as shown in Fig. 1. These values are then used to determine the residual stress parallel to the surface, σ_ϕ (the direction of σ_ϕ is in the same plane as ε_z and $\varepsilon_{\phi\psi}$).

The conversion of the measured elastic strains to residual stress uses classical elasticity theory giving the result that:

$$\sigma_\phi = (\varepsilon_{\phi,\psi} - \varepsilon_z) \frac{E}{\nu+1} \cdot \frac{1}{\text{Sin}^2\psi} \qquad (1)$$

where E = elastic modulus

ν = Poisson's ratio

and ψ = angle between $\varepsilon_{\phi,\psi}$ and ε_z

Procedure

The angular position, $2\theta,_{\psi} = 0^\circ$, for a high-angle diffraction line is determined for the test sample in its normal orientation in a diffractometer (see Fig. 2(a)). This leads to a value for ε_z. The sample is then rotated about the diffractometer axis by an appropriate value of ψ as shown in Fig. 2 (b). This in turn leads to a value for $\varepsilon_{\phi,\psi}$ as determined by the position $2\theta_{\psi=\psi}$ of the same high-angle diffraction line.

A high-angle diffraction line is necessary because only such lines are:

(a) sufficiently sensitive to residual stresses; and

(b) capable of allowing a reasonable rotation, ψ, of the sample.

In the case of steels the 211 ferrite/martensite line which occurs at $2\theta \approx 156^\circ$ for chromium K_α radiation is a suitable choice.

The accuracy of diffraction line location, 2θ, is the critical factor which controls the precision of the technique. It has been found that the use of step-scanning with associated least-squares curve-fitting gives the most satisfactory results. In this method the variation of diffracted intensity near to the peak is measured at a number of small angular steps. The turning-point of a least-square polynomial fitted to these data is taken as the position of the diffraction line. A vertical-axis quadratic is a satisfactory polynomial for most diffraction lines.

A number of experimental factors must be taken into account when measuring residual stresses using X-ray techniques. These include:

(1) surface preparation effects; and

(2) sample location particularly in the case of large components.

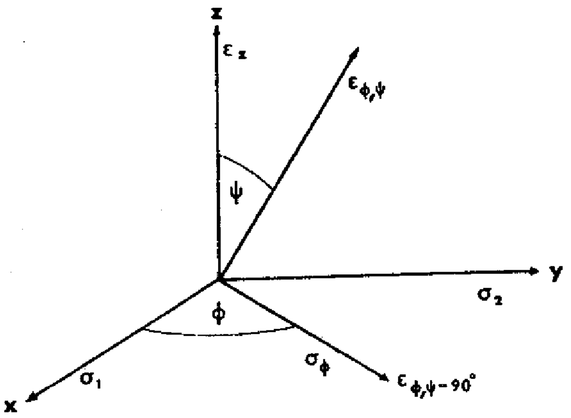


Fig. 1. Symbols used in X-ray stress analysis

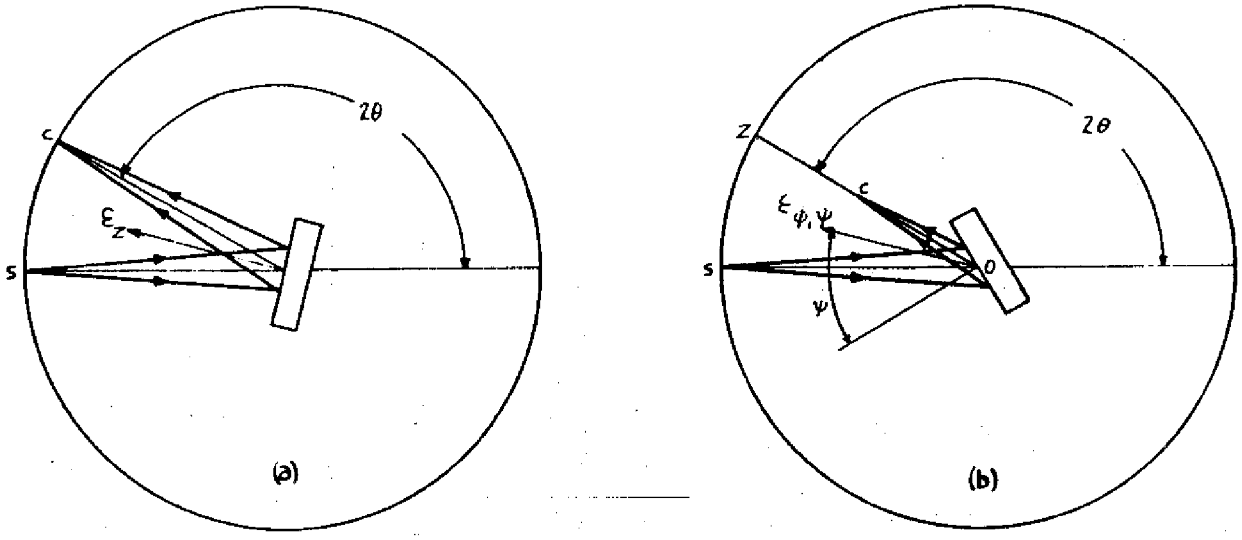


Fig. 2. Focussing geometry for flat samples (a) when $\psi - 0^{\circ}$ and (b) when $\psi - 45^{\circ}$. The X-ray source is at S, and the counter should be at C for optimum intensity measurements.

TABLE I SPRING DESIGNS

MATERIAL	BS 1408M Range 2		BS 2803 Grade II		BS 2056 (En 58A)	
Wire Diameter (mm)	1.63	3.15	4.00	5.74	1.22	5.89
Mean Coil Diameter (mm)	11.4	24.5	30.0	40.1	9.75	44.2
Spring Index	7.0	8.0	7.5	7.0	8.0	7.5
Total coils	5.5	5.5	5.5	5.5	7.5	5.3
Active coils	3.5	3.5	3.5	3.5	5.5	3.3
Free Length (mm) (after prestressing)	23.4	48.0	50.0	68.2	28.9	65.0
Spring Rate (N/mm)	13.5	17.4	27.0	47.4	4.0	38.5
Solid Stress (N/mm^2)	1517	1200	1100	1100	1270	830

TABLE II AVERAGE SHOT HARDNESS

SHOT SIZE	HARDNESS
S550	480 HV30
S460	455 HV30
S330	455 HV20
S230	465 HV10
S110	365 HV5
S70	310 HV2½

TABLE III SURFACE FINISH MEASUREMENT ON ALMEN STRIPS

SHOT SIZE	AVERAGE CLA VALUE (μm)
S550	3.8
S460	2.9
S330	2.7
S230	2.0
S110	1.9
S70	1.3
Unpeened	0.7

TABLE IV SUMMARY OF SHOT SIZE SPECIFICATION, S.A.E. J444

Sieve Size	SHOT SIZE					
(in)	S550	S460	S330	S230	S110	S70
0.0787	All pass	All pass	-	-	-	-
0.0661	-	5% max	-	-	-	-
0.0551	85% min	-	All pass	-	-	-
0.0469	97% min	85% min	5% max	-	-	-
0.0394	-	96% min	-	All pass	-	-
0.0331	-	-	85% min	10% max	-	-
0.0280	-	-	96% min	-	-	-
0.0232	-	-	-	85% min	All pass	-
0.0197	-	-	-	97% min	10% max	-
0.0165	-	-	-	-	-	All pass
0.0138	-	-	-	-	-	10% max
0.0117	-	-	-	-	80% min	-
0.0070	-	-	-	-	90% min	80% min
0.0049	-	-	-	-	-	90% min

TABLE V AVERAGE FREE LENGTH OF SPRINGS FROM 1.63 mm DIAMETER WIRE TO BS 1408M RANGE 2 AFTER PEENING

Free Length (mm)	UNPEENED SPRINGS	SHOT SIZE					
		S70	S110	S230	S330	S460	S550
After shot peening	-	30.7	30.7	30.6	30.6	30.6	30.6
After shot peening and L.T.H.T.	-	30.8	30.8	30.7	30.6	30.6	30.6
After prestressing	23.4	23.4	23.4	23.4	23.5	23.4	23.4

TABLE VI AVERAGE FREE LENGTH OF SPRINGS FROM 3.15 mm DIAMETER WIRE TO BS 1408M RANGE 2 AFTER PEENING

FREE LENGTH (mm)	UNPEENED SPRINGS	SHOT SIZE					
		S70	S110	S230	S330	S460	S550
After shot peening	-	51.3	51.2	51.6	51.1	51.4	51.2
After shot peening and L.T.H.T.	-	51.3	51.2	51.5	51.3	51.4	51.2
After prestressing	48.4	47.8	47.8	47.6	47.5	48.3	48.0

TABLE VII AVERAGE FREE LENGTH OF SPRINGS FROM 5.75 mm DIAMETER WIRE TO BS 2803 GRADE II AFTER PEENING

FREE LENGTH (mm)	UNPEENED SPRINGS	SHOT SIZE					
		S70	S110	S230	S330	S460	S550
After shot peening	-	73.0	72.7	72.9	72.8	72.8	72.9
After shot peening and L.T.H.T.	-	73.0	72.7	72.8	72.8	72.8	72.8
After prestressing	68.5	68.0	68.3	68.2	68.3	68.0	68.1

TABLE VIII AVERAGE FREE LENGTH OF SPRINGS FROM 5.9 mm DIAMETER WIRE TO En 58A (BS 2056) AFTER PEENING

Free Length (mm)	UNPEENED SPRINGS	SHOT SIZE				
		S70	S230	S330	S460	S550
After shot peening	-	68.3	67.6	67.7	67.7	67.7
After shot peening and L.T.H.T.	-	68.0	67.6	67.7	67.7	67.8
After prestressing	65.4	65.4	64.7	64.9	64.9	64.9

TABLE IX SURFACE RESIDUAL STRESS LEVELS IN ALMEN STRIPS AFTER RELEASE

SPECIMEN	SHOT SIZE	ALMEN ARC RISE (in)	RESIDUAL STRESS (N/mm^2)	
			σ_x	σ_y
A	S70	0.005	-432	-370
B	S70	0.005	-378	-436
C	S110	0.008	-436	-472
D	S110	0.007	-419	-461
E	S230	0.011	-301	-458
F	S230	0.012	-245	-421
G	S330	0.017	-225	-430
H	S330	0.019	-212	-409
I	S460	0.022	-146	-370
J	S460	0.023	-150	-323
K	S550	0.026	-116	-319
L	S550	0.028	-94	-304

σ_x = parallel to long axis of strip

σ_y = parallel to short axis of strip

TABLE X SURFACE RESIDUAL STRESS LEVELS IN ALMEN STRIPS 'AS CLAMPED'

SPECIMEN	RADII (mm)		STRESS RELIEVED BY BENDING (N/mm^2)		RESIDUAL SURFACE STRESS 'AS CLAMPED' (N/mm^2)		ALMEN ARC RISE	
	R_x	R_y	σ_x	σ_y	Σ_x	Σ_y	(in)	(mm)
A	1520	960	-139	-178	-571	-548	0.005	0.13
B	1470	910	-145	-188	-523	-624	0.005	0.13
C	1070	740	-194	-236	-630	-708	0.008	0.20
D	1020	740	-200	-239	-619	-700	0.007	0.18
E	790	300	-325	-529	-626	-987	0.011	0.28
F	690	300	-352	-536	-597	-957	0.012	0.30
G	460	300	-457	-568	-682	-998	0.017	0.43
H	430	250	-505	-669	-717	-1078	0.019	0.48
I	380	230	-568	-745	-714	-1115	0.022	0.56
J	330	230	-568	-745	-718	-1068	0.023	0.58
K	360	200	-619	-832	-735	-1151	0.026	0.66
L	330	180	-680	-943	-774	-1247	0.028	0.71

TABLE XI EFFECT OF WHEEL SPEED ON ALMEN STRIP PARAMETERS

WHEEL SPEED (Hz)	WHEEL VELOCITY m/sec	ALMEN ARC RISE (in)	ALMEN ARC RISE (mm)	AVERAGE CLA VALUE (μm)	RESIDUAL SURFACE STRESS (N/mm^2)		RESULTANT SURFACE STRESS 'AS CLAMPED' (N/mm^2)	
					σ_x	σ_y	Σ_x	Σ_y
25	24	0.014	0.36	2.3	-270	-385	-620	-920
37.5	36	0.017	0.43	2.7	-225	-430	-682	-998
48.3	46	0.022	0.56	3.4	-180	-390	-705	-1065

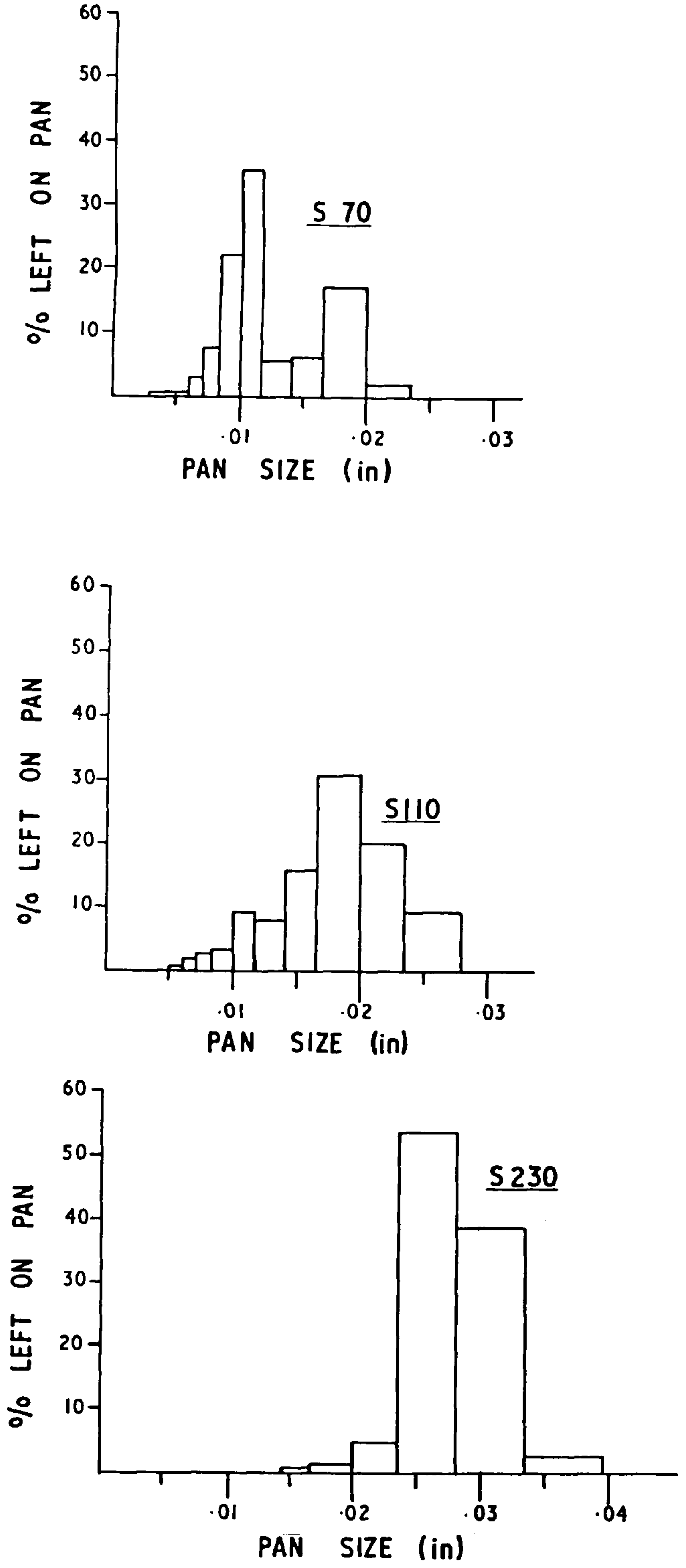


FIG. 1 SHOT SIZE DISTRIBUTION – S 70 S 110 & S 230.

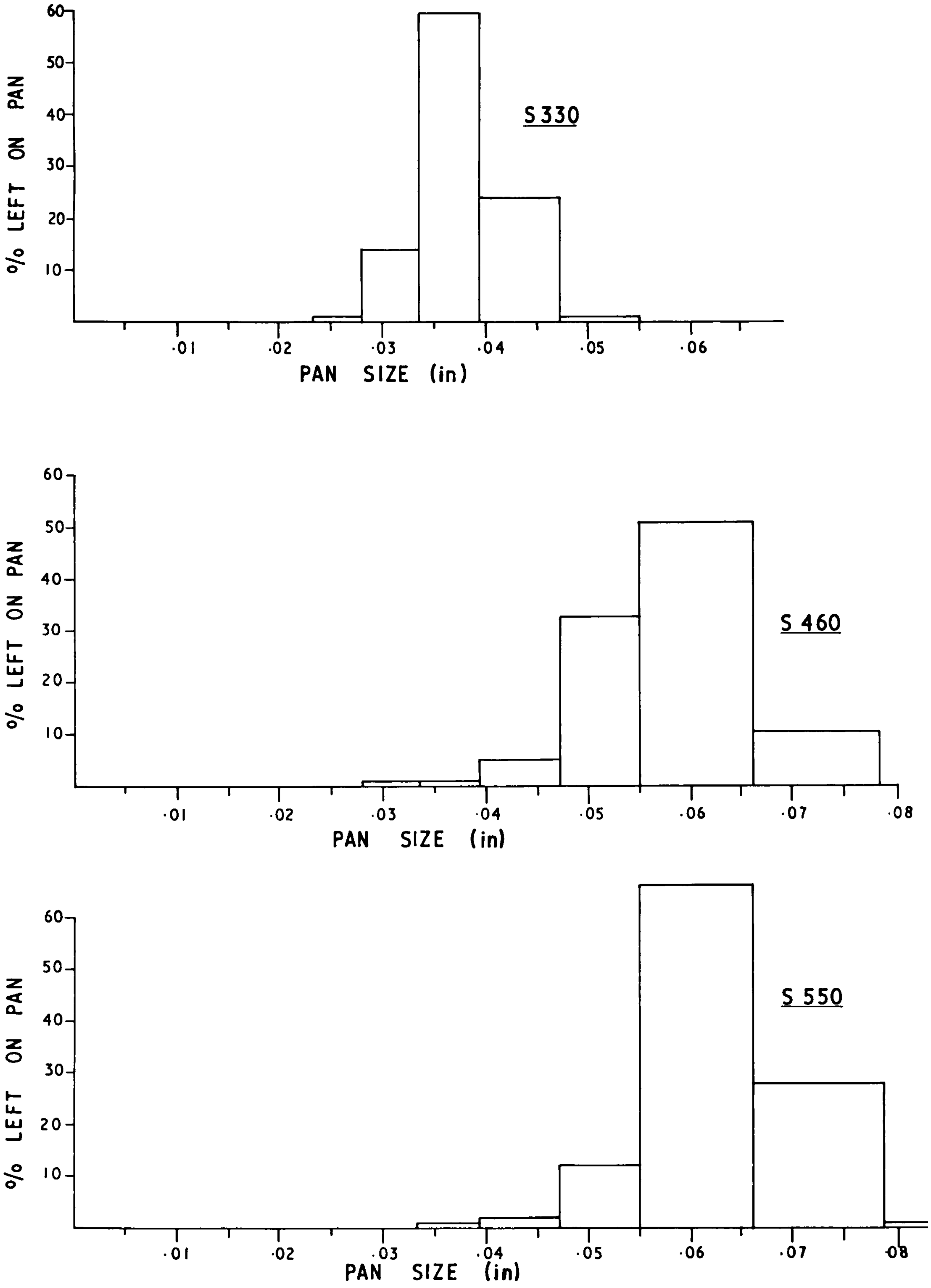


FIG. 2 SHOT SIZE DISTRIBUTION – S330, S460, S550.

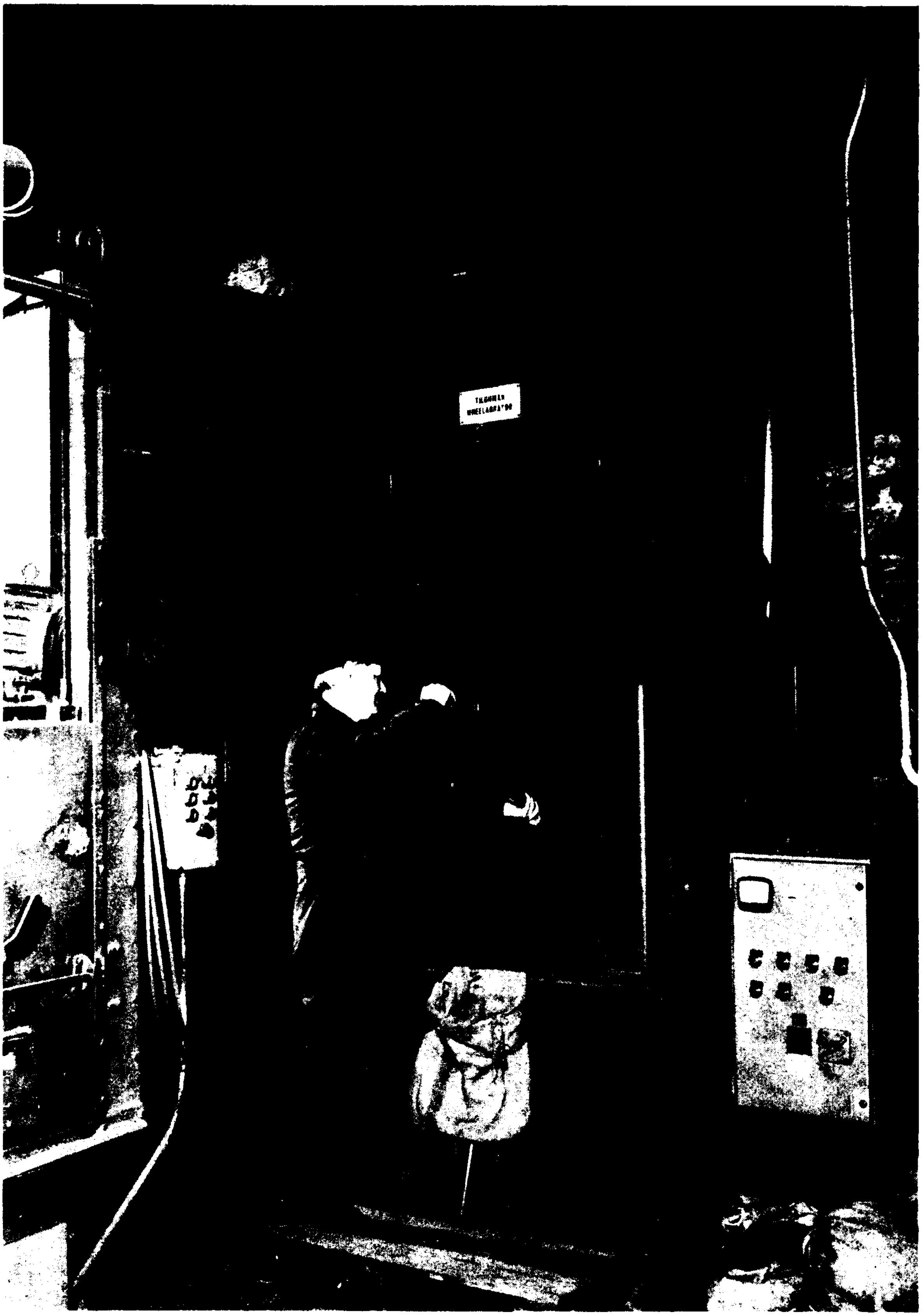
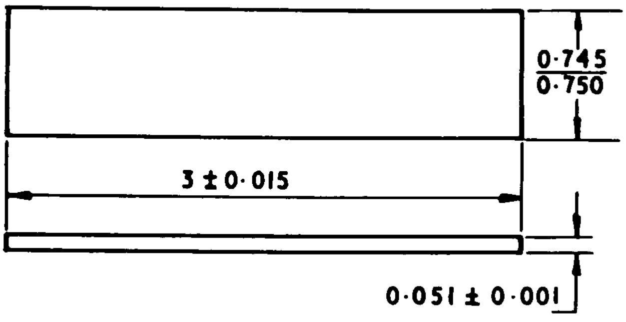


FIG. 3. TILGHMAN WHEELABRATOR 'TUMBLAST' MACHINE.



ALMEN 'A' TEST STRIP

(DIMENSIONS IN INCHES)

ANALYSIS OF STOCK - SAE 1070

COLD ROLLED SPRING STEEL

SQUARE EDGE NUMBER ONE (ON 3" EDGES)

FINISH — BLUE TEMPER (OR BRIGHT)

UNIFORMLY HARDENED AND TEMPERED TO 44-50 RC

FLATNESS - ± ·0015" ARC HEIGHT AS MEASURED ON A STANDARD ALMEN No. 2 GAUGE

FIG. 4 ALMEN TEST STRIP SPECIFICATION

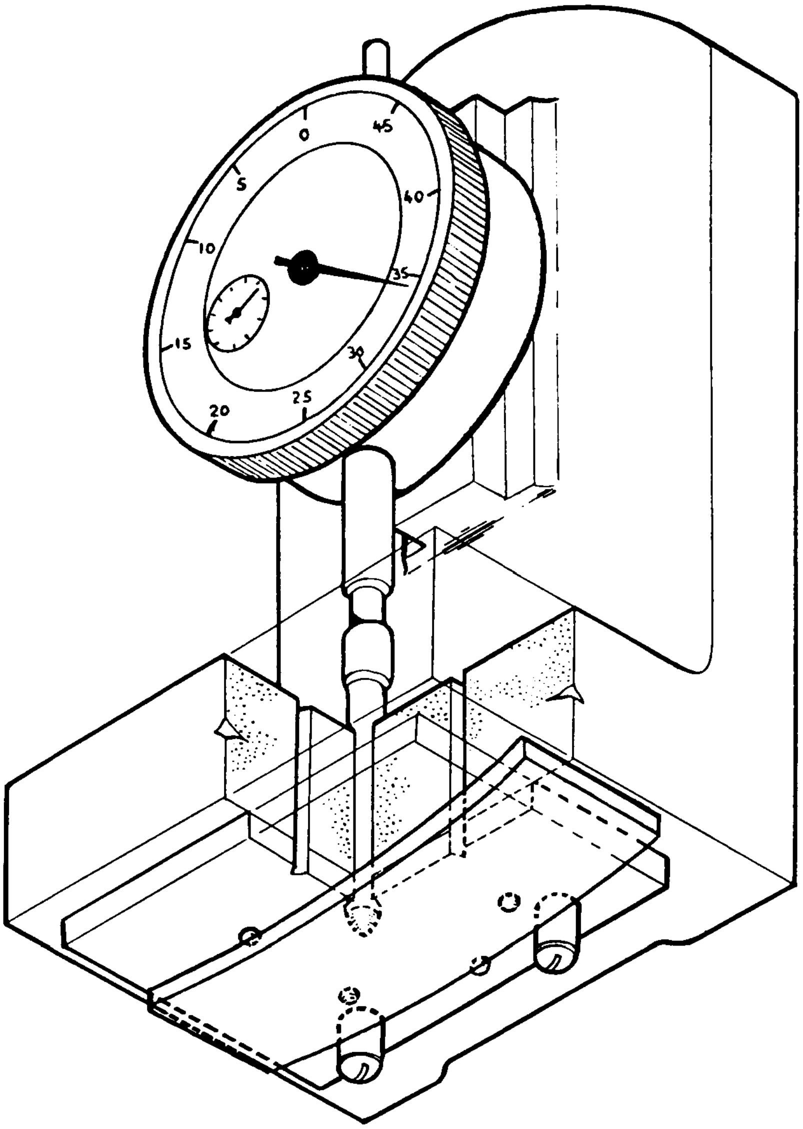


FIG. 5 ALMEN No. 2 GAUGE.

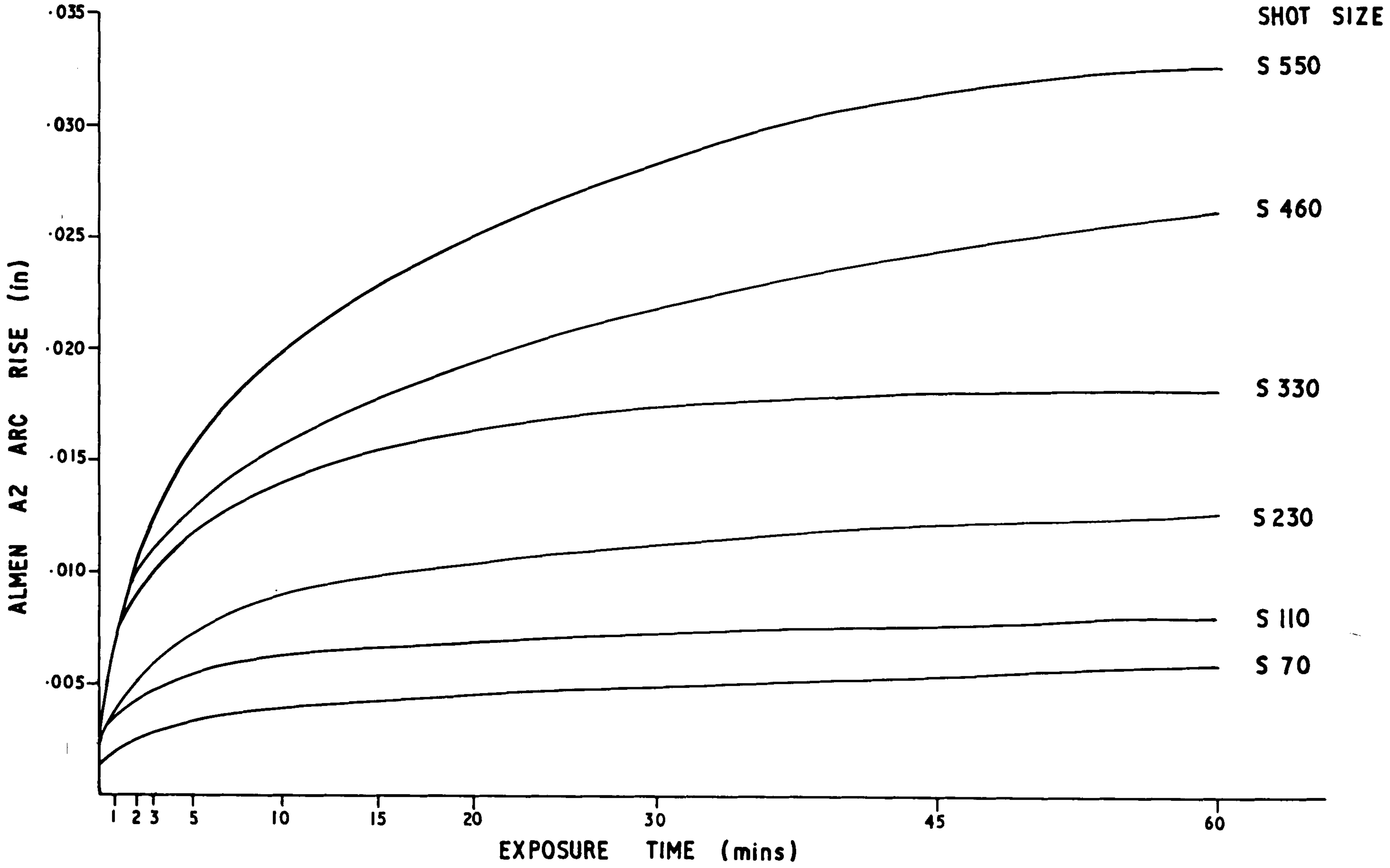


FIG. 6 CALIBRATION CURVE OF SHOT AT NORMAL WHEEL SPEED (37·5 Hz)

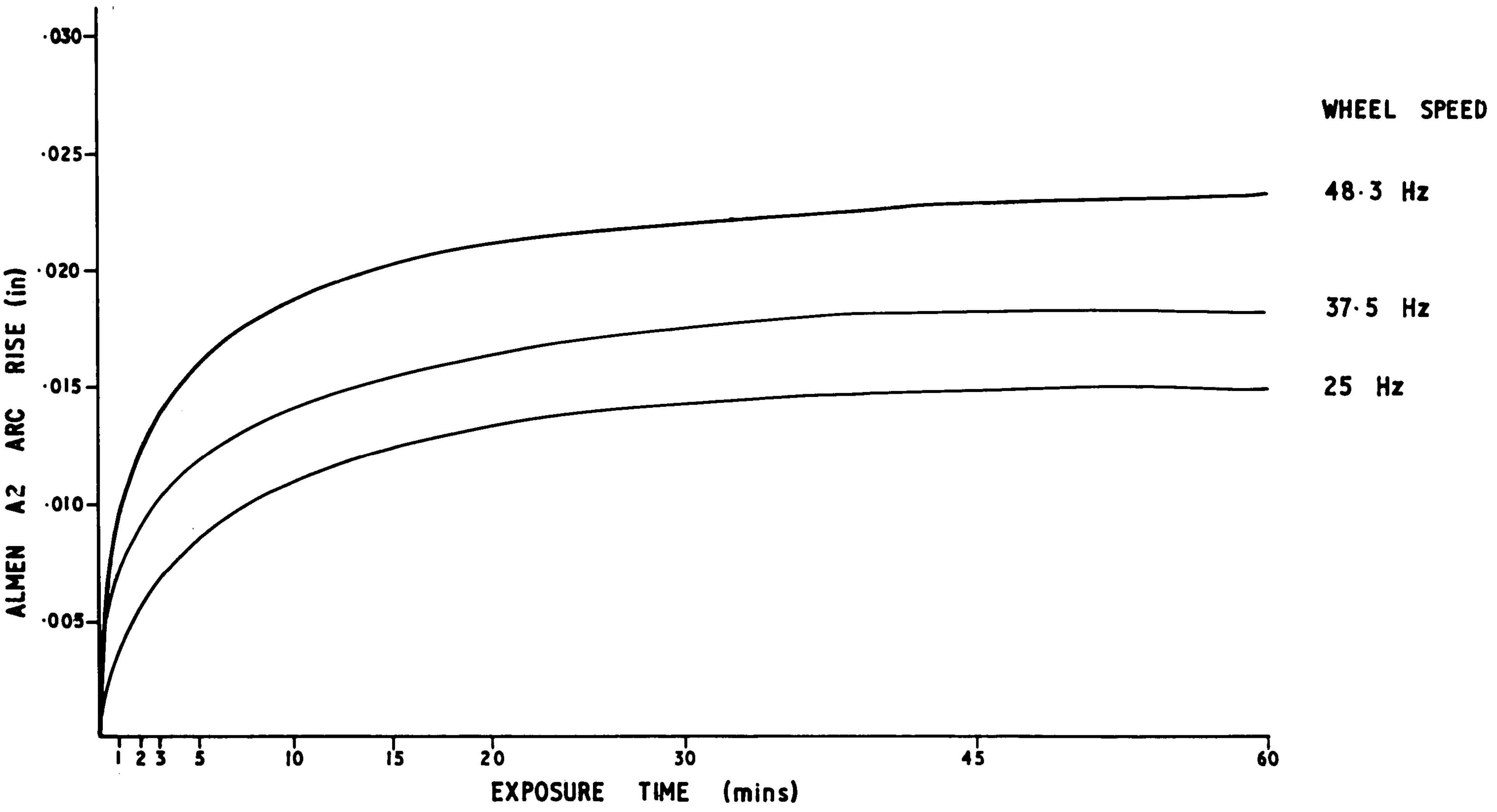


FIG. 7 CALIBRATION CURVE OF S330 SHOT AT DIFFERENT WHEEL SPEEDS.

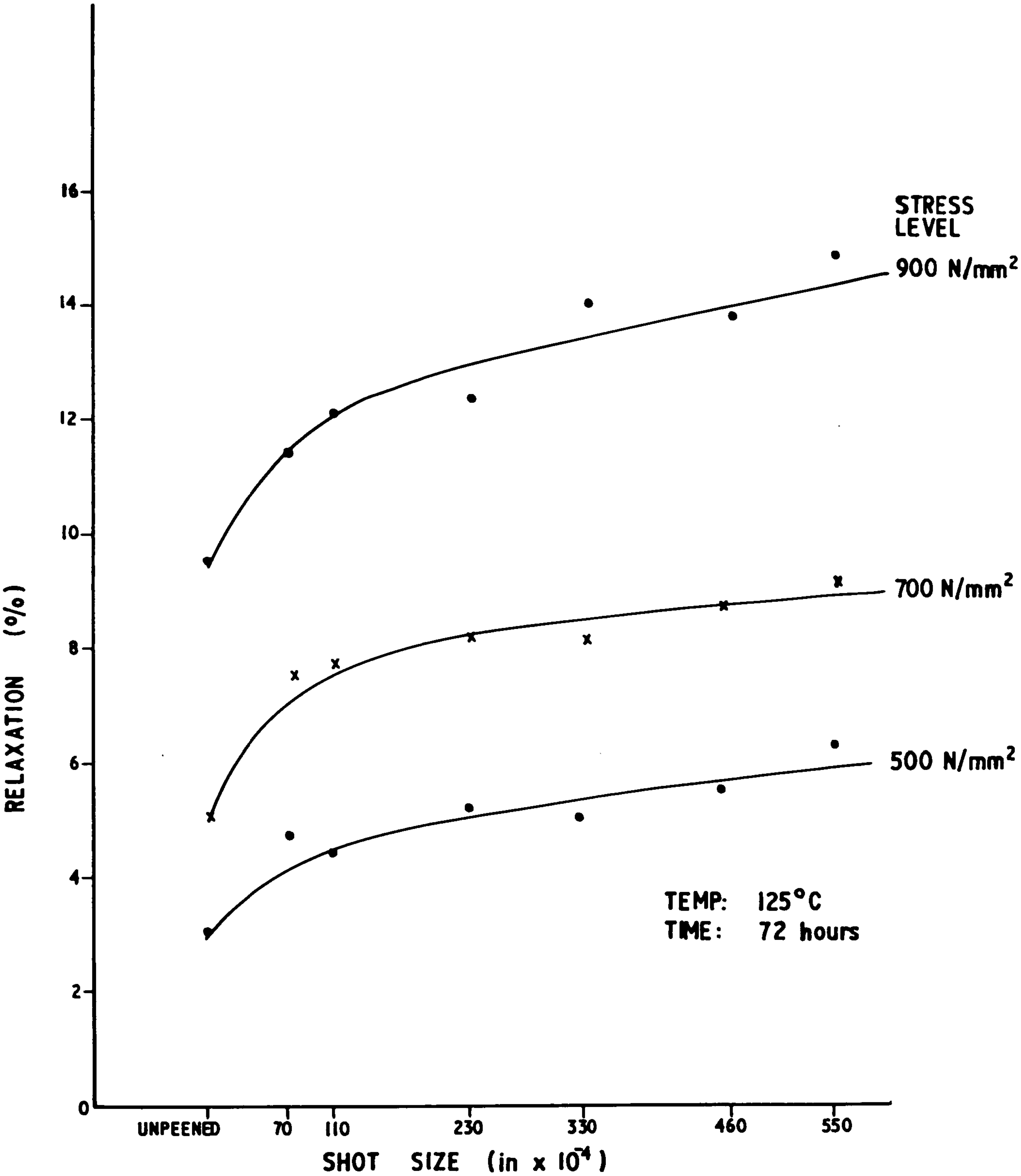


FIG. 8 STRESS - RELAXATION TESTS - 3·15 mm DIA. BS 1408 M RANGE 2 SPRINGS.

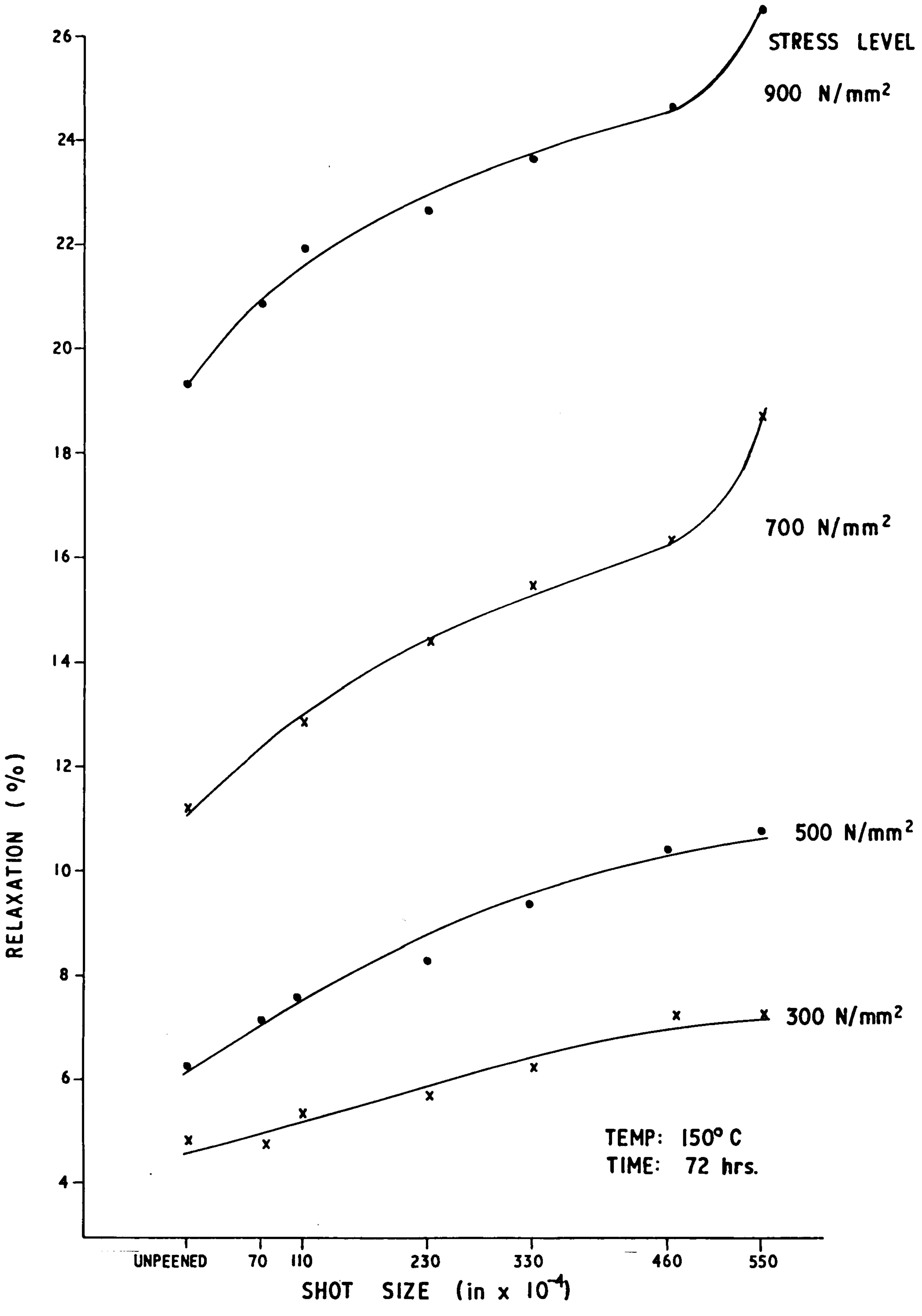


FIG. 9 STRESS RELAXATION TESTS - 4·0 mm DIA. BS 2803 SPRINGS

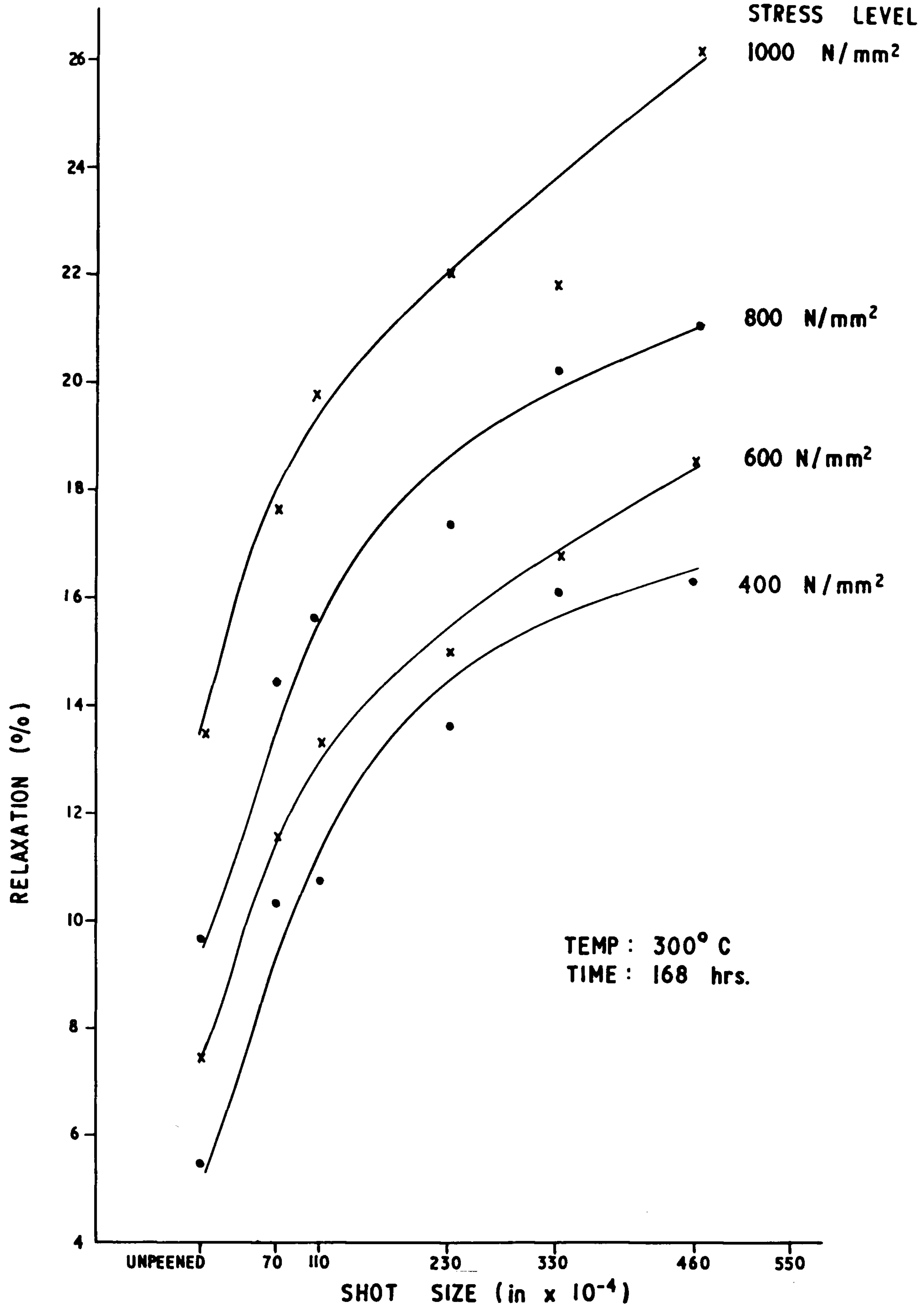


FIG. 10 STRESS-RELAXATION TESTS - 1·22 mm DIA. En 58 A SPRINGS.

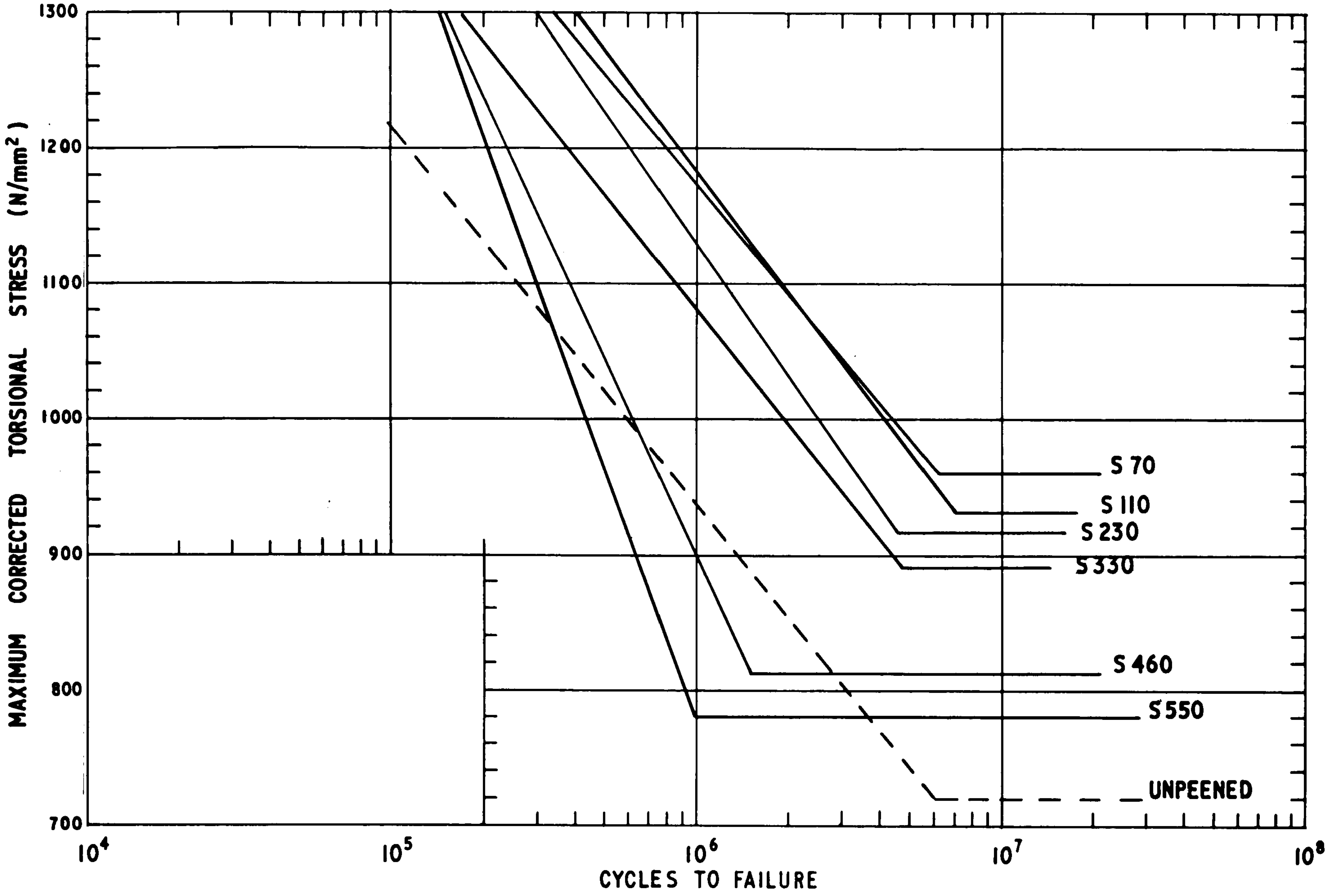


FIG. 11 S/N CURVE FOR SPRINGS FROM 1·63 mm DIA. WIRE TO BS 1408 M RANGE 2.

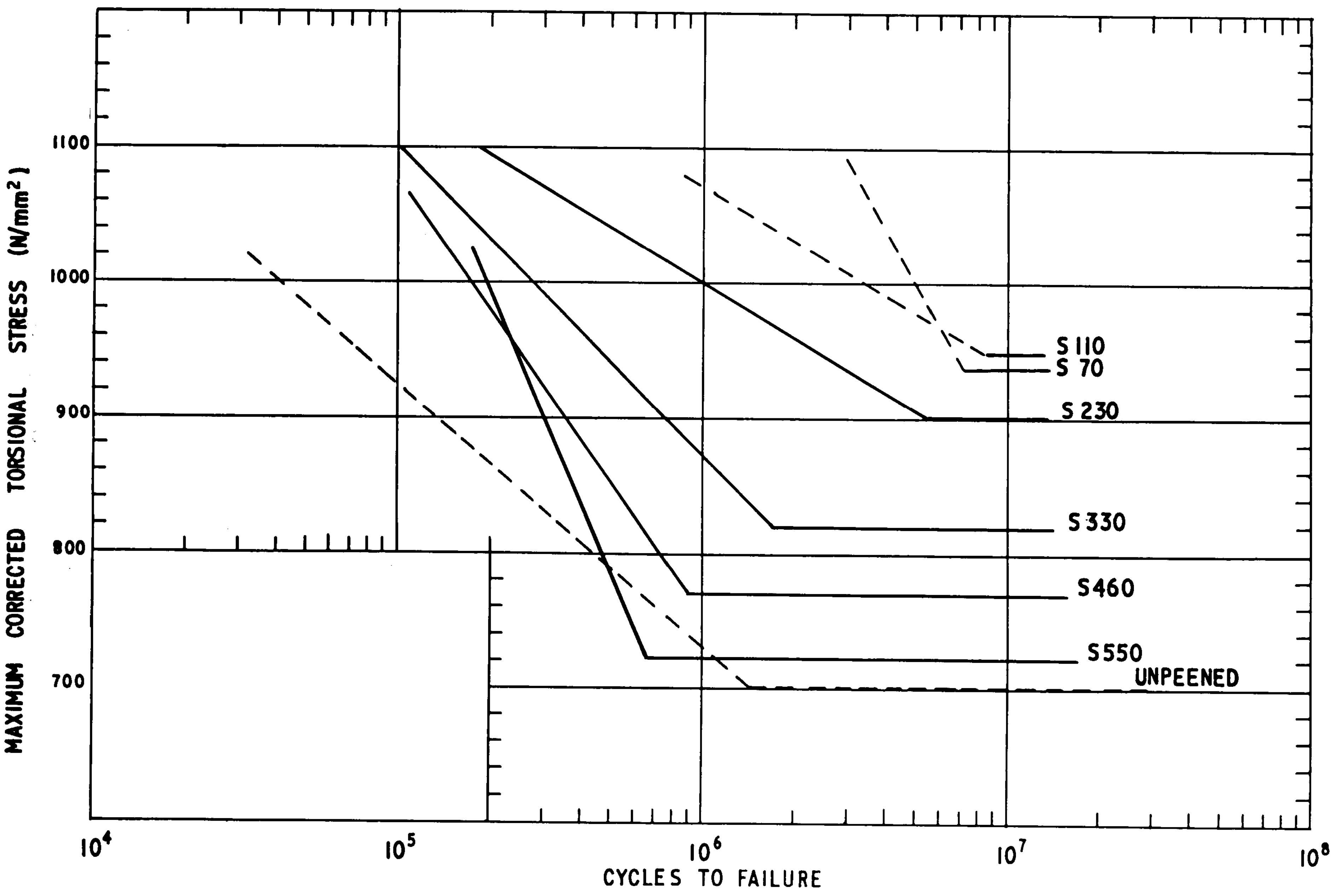


FIG. 12 S/N CURVE FOR SPRINGS FROM 3·15 mm DIA. WIRE TO BS 1408 M RANGE 2.

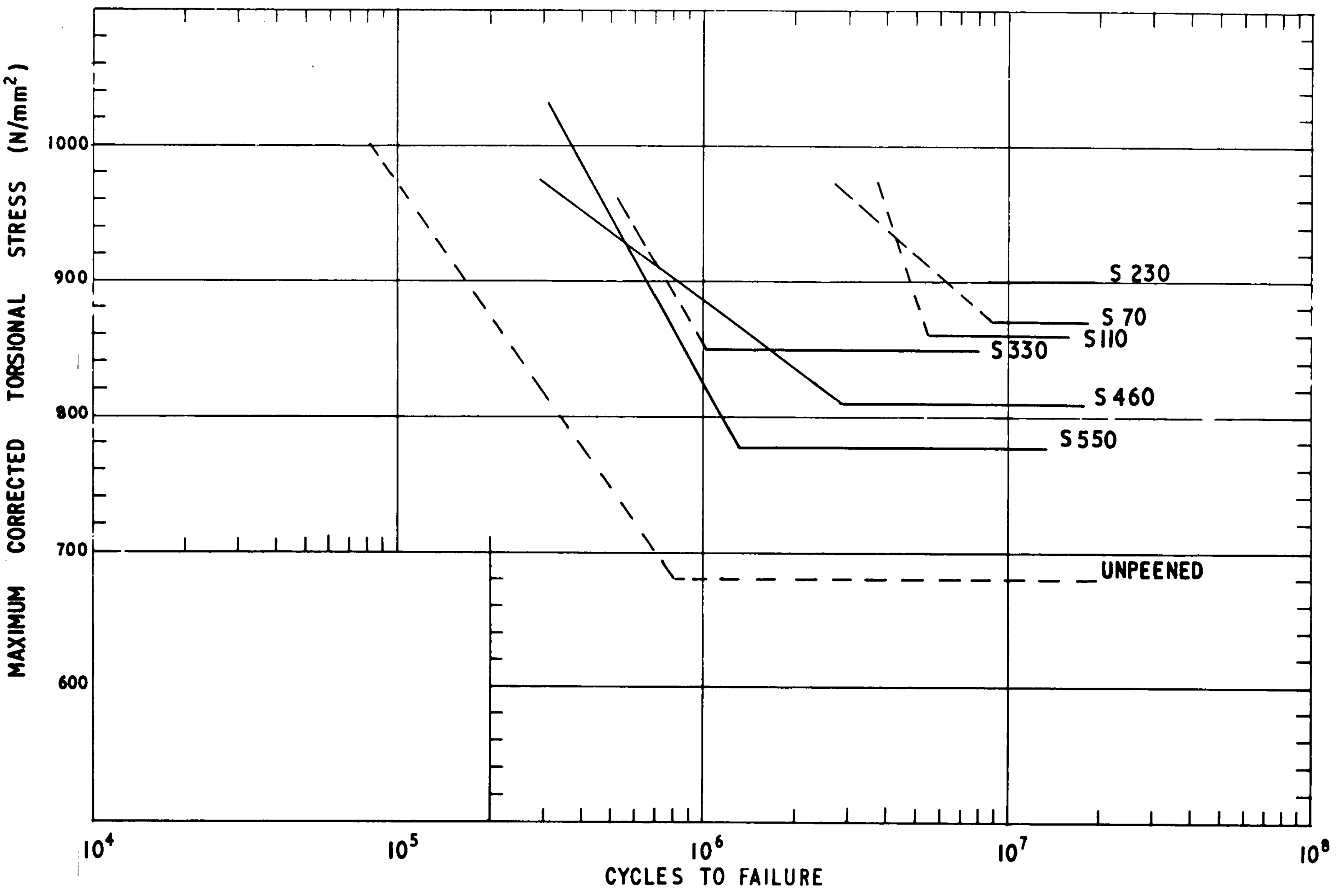


FIG. 13 S/N CURVE FOR SPRINGS FROM 5·74 mm DIA. WIRE TO BS 2803.

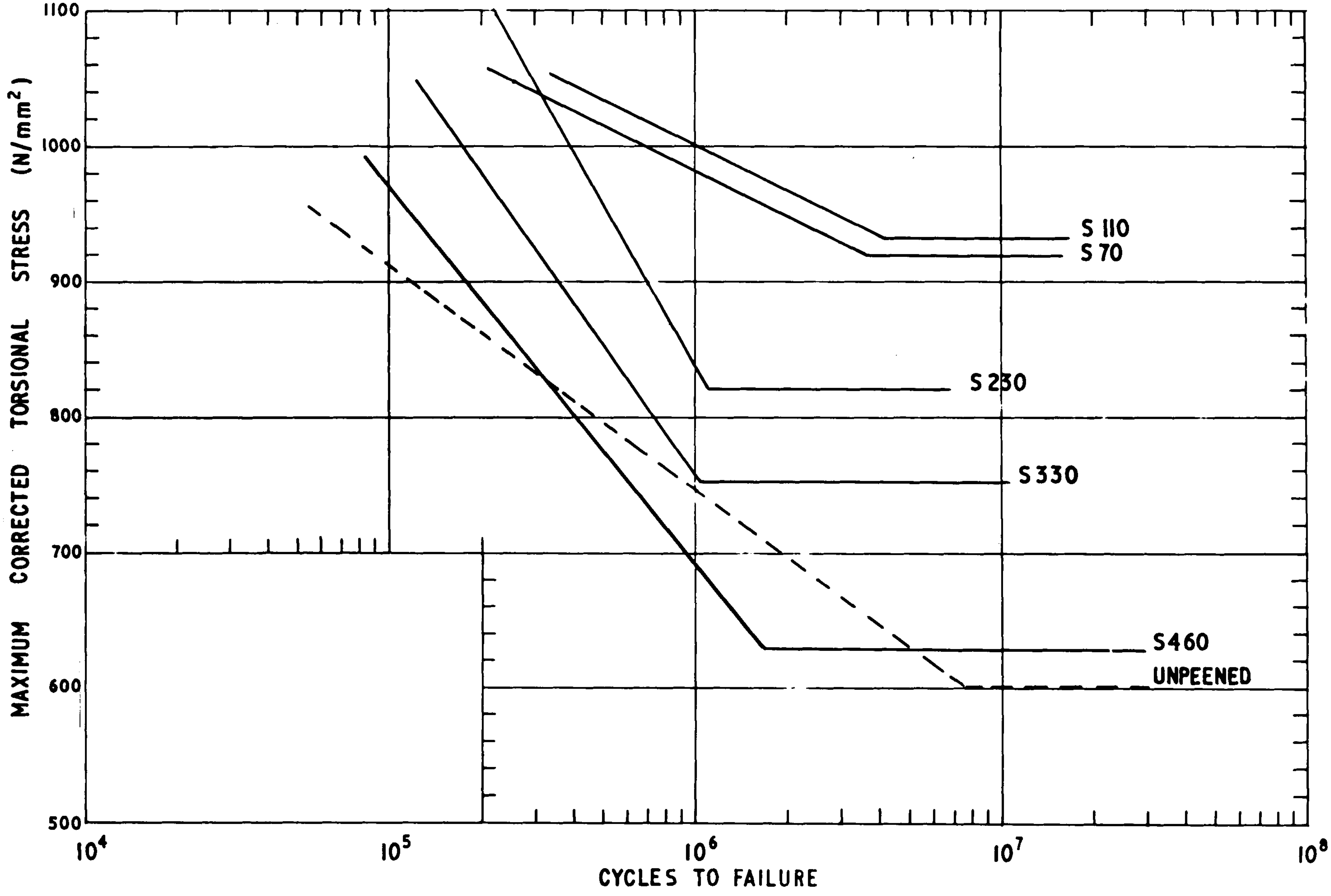


FIG. 14 S/N CURVE FOR SPRINGS FROM 1·22 mm DIA. WIRE TO BS 2056 (En 58 A)

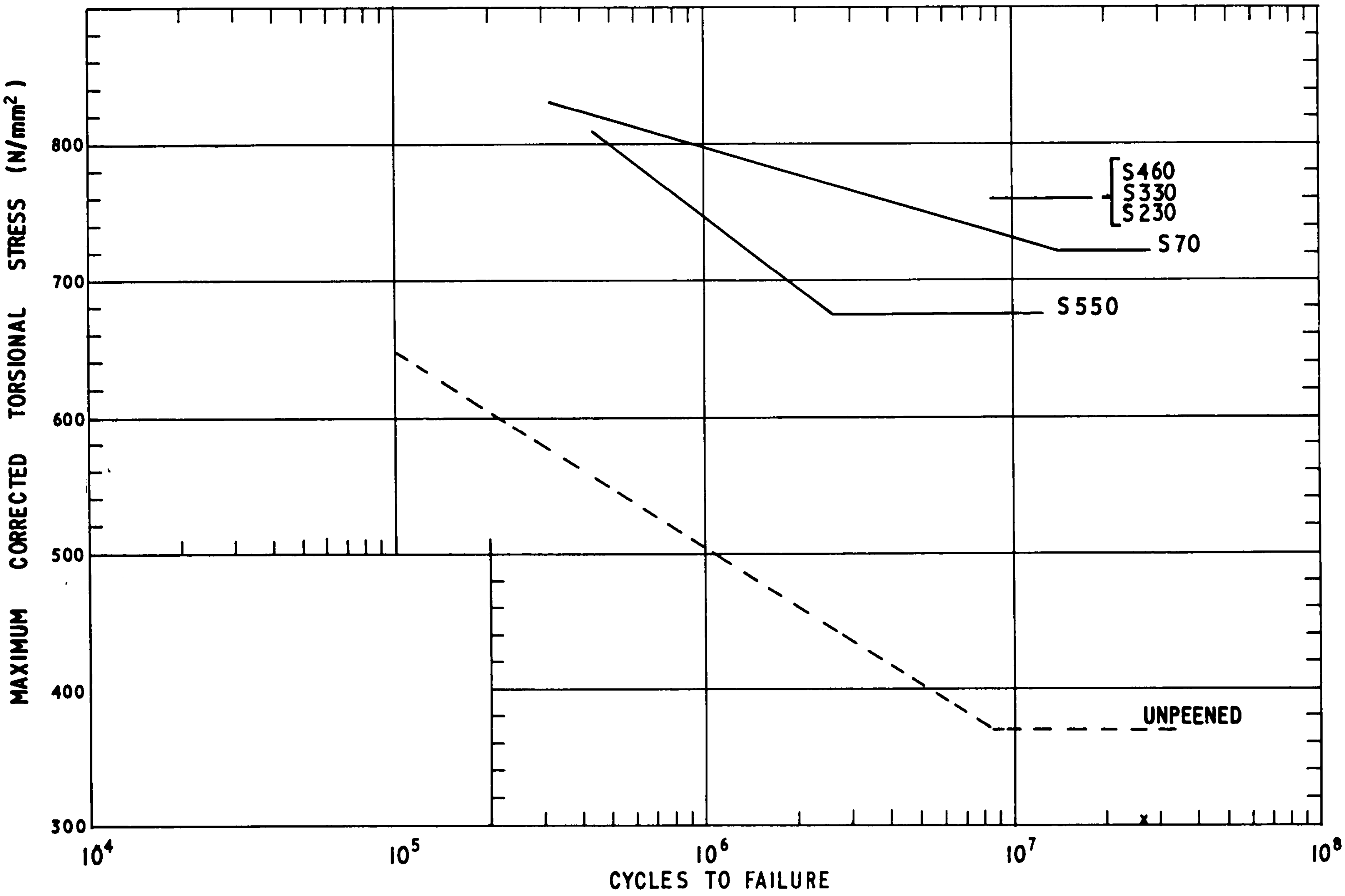


FIG. 15 S/N CURVE FOR SPRINGS FROM 5·89 mm DIA. WIRE TO BS 2056 (En 58A)

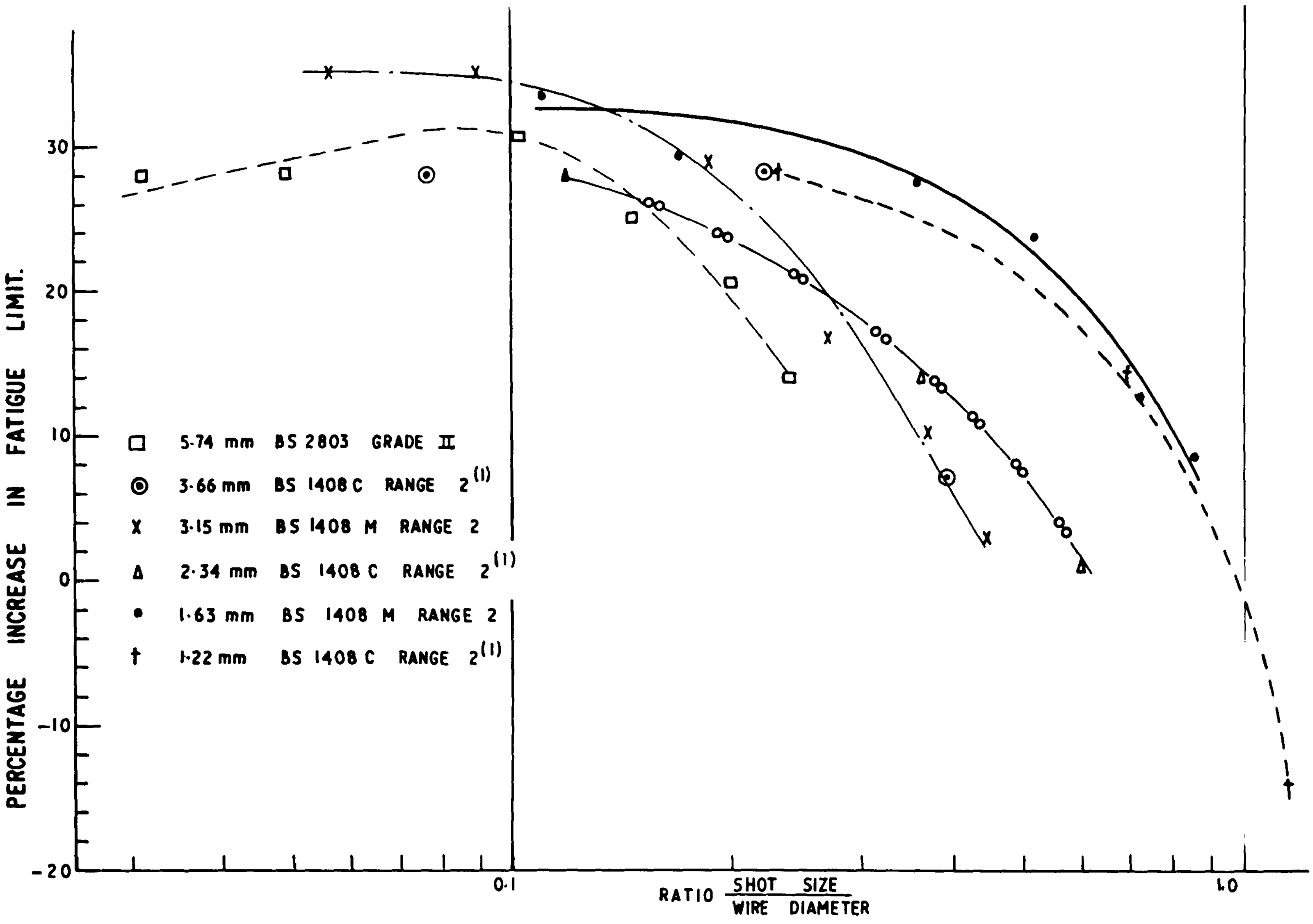


FIG. 16 SUMMARY OF FATIGUE DATA FOR CARBON STEEL SPRINGS.

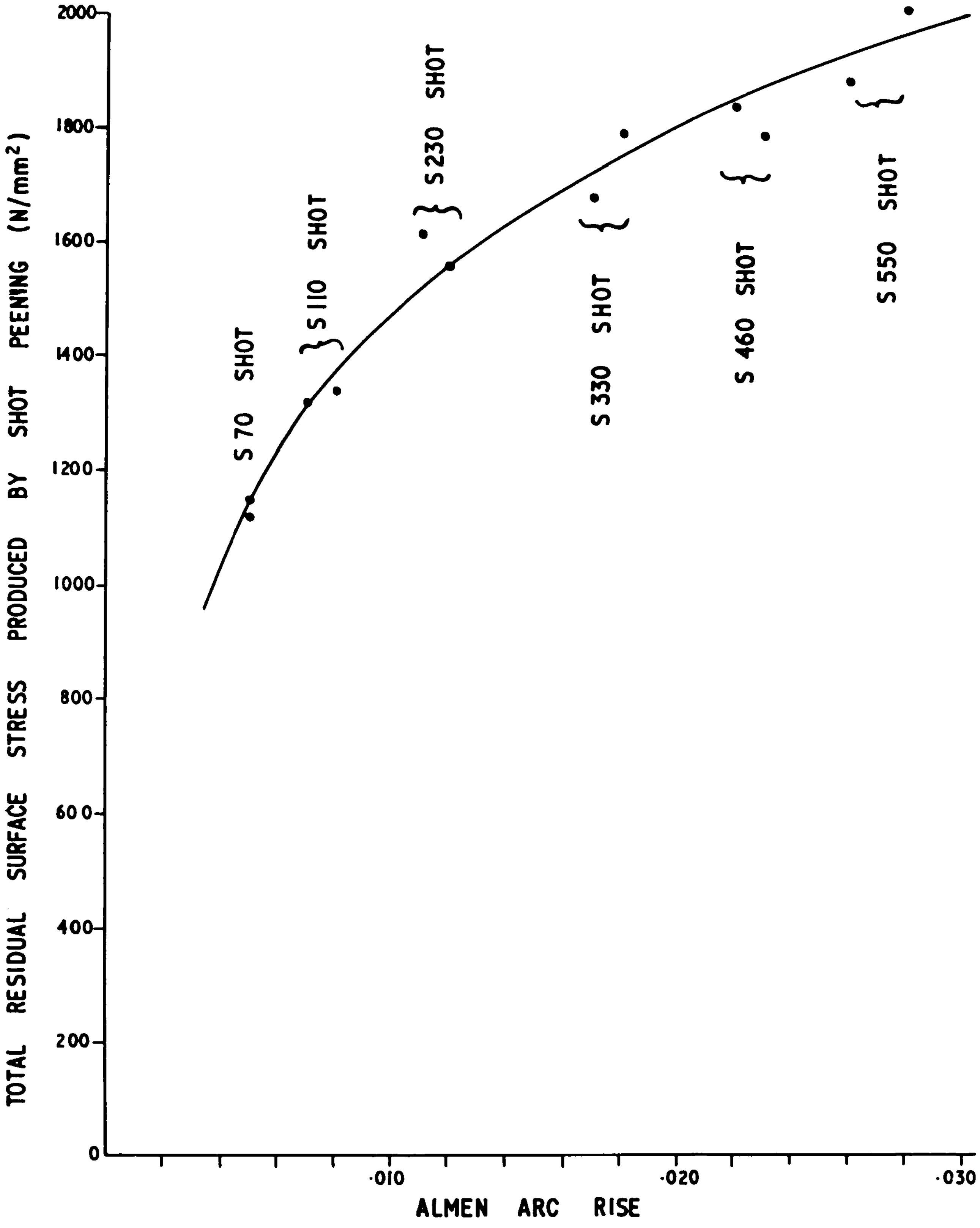


FIG. 17 RESIDUAL SURFACE STRESSES INDUCED BY SHOT PEENING.

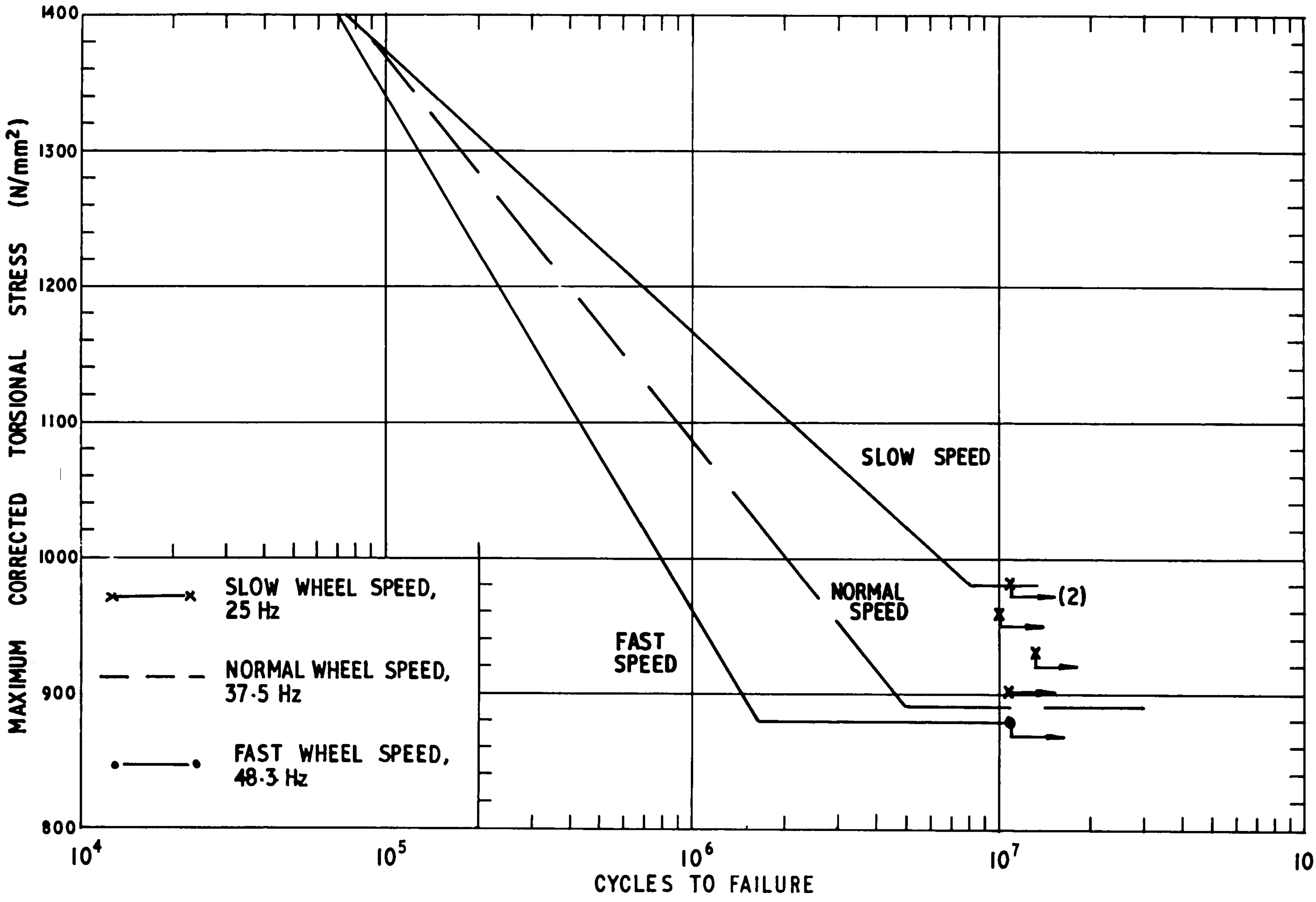


FIG. 18 S/N CURVE FOR 1·63 mm DIA. SPRINGS TO BS 1408 M R2 PEENED WITH S330 SHOT AT DIFFERENT WHEEL SPEEDS.

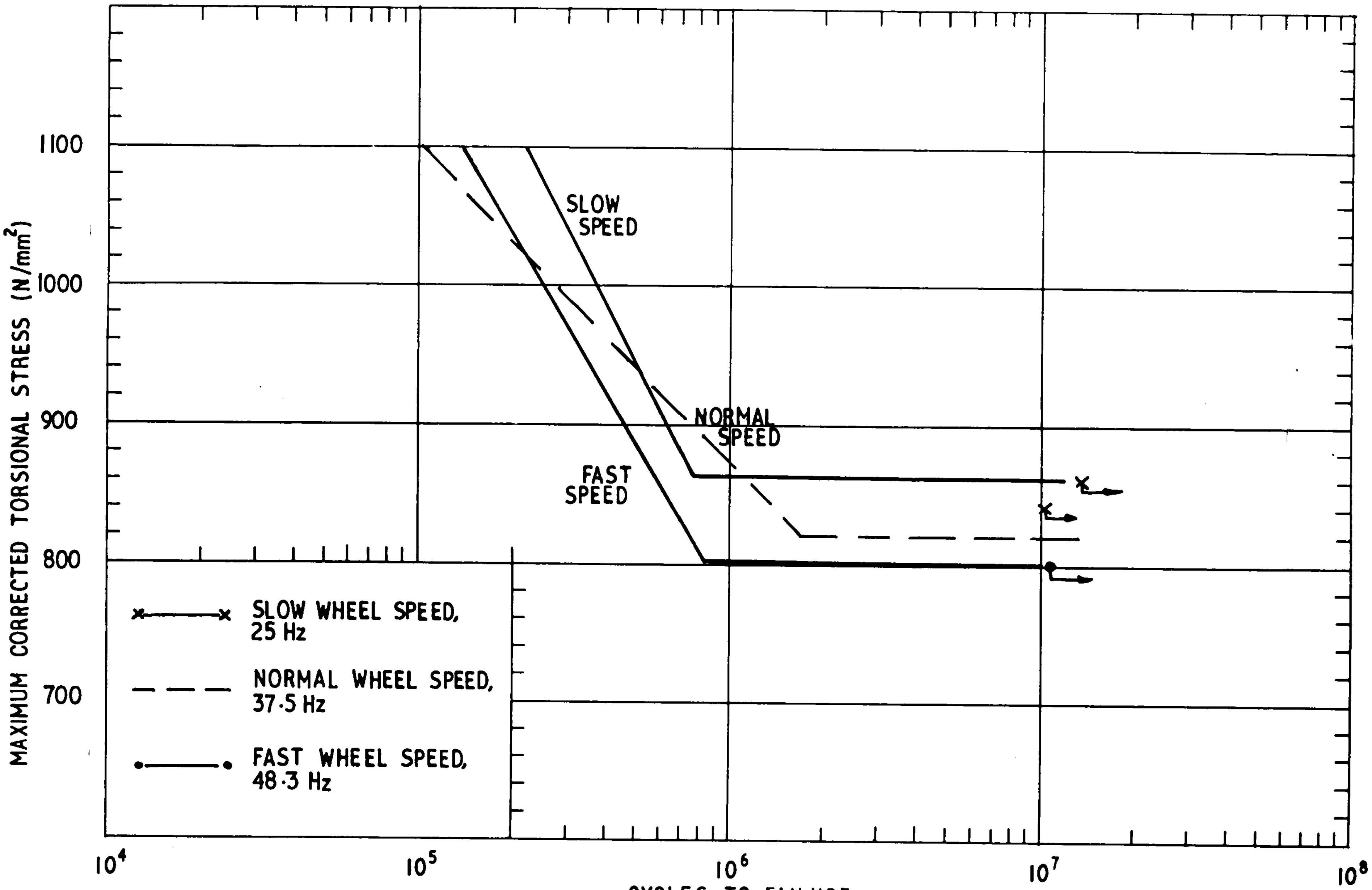


FIG. 19 S/N CURVE FOR 3.15mm DIA. SPRINGS TO BS 1408M RANGE 2 PEENED WITH S330 SHOT AT DIFFERENT WHEEL SPEEDS